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CHILL STORAGE AND HEAT-ACTIVATED REFRIGERATION USING COMPLEX-COMPOUND SORPTION

by
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July 1999

Final Report
April 1995 - February 1999

Prepared for
U. S. Army Soldier and Biological Chemical Command
Soldier Systems Center
Natick, Massachusetts 01760-5018

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1999	FINAL April 1995 - February 1999

4. TITLE AND SUBTITLE
CHILL STORAGE AND HEAT-ACTIVATED REFRIGERATION USING COMPLEX-COMPOUND SORPTION

5. FUNDING NUMBERS
C DAAK60-95-C-2031

6. AUTHOR(S)
Lance Kirol

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Rocky Research
1598 Foothill Drive
Boulder City, NV 89005

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Soldier and Biological Chemical Command
Soldier Systems Center
ATTN: AMSSB-RCF-E(N)
Natick, MA 01760-5018

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
NATICK/TR-99/029

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report documents the design and testing of a field refrigerator that has been delivered to the U. S. Army Soldier Systems Center, Soldier and Biological Chemical Command, as the culmination of a four-phase Broad Agency Announcement (BAA) project that started in April 1995. The refrigerator is intended as a possible replacement for the ice box currently used in the Mobile Kiltchen Trailer (MKT).

14. SUBJECT TERMS

CHILL STORAGE	MOBILE KITCHEN TRAILER	DIESEL-FIRED
HEAT ACTIVATED	MKT(MOBILE KITCHEN TRAILER)	SELF CONTAINED
REFRIGERATORS	PERIODIC CHARGING	ELECTRICAL POWER

15. NUMBER OF PAGES
64

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

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PREFACE

This report documents the design and testing of a field refrigerator that has been delivered to the U.S.Army Natick R&D Center (now Soldier and Biological Chemical Command/Soldier Systems Center) as the culmination of a four-phase Broad Agency Announcement (BAA) project, Contract DAAK60-95-C-2031 that started in April, 1995. The refrigerator is intended as a possible replacement for the ice box currently used in the Mobile Kitchen trailer (MKT).

CHILL STORAGE AND HEAT-ACTIVATED REFRIGERATION USING COMPLEX-COMPOUND SORPTION

INTRODUCTION

Contract DAAK60-95-C-2031 started in April, 1995 as a four-phase project. The first two phases were to focus on development of a field refrigerator using complex compound chill storage, and recharged using an M2 field burner and pressure cooker. No electrical power consumption was allowed for operation or recharge of the refrigerator. These two phases were completed as originally contracted. Phases III and IV were modified[1] to provide for development of a field refrigerator similar to the Phase I/II device, except recharging was to be accomplished with a built-in diesel heater, and use of electrical power during recharging was acceptable. Phases III and IV were combined into a single deliverable, a 6.3 ft^3 field refrigerator with chill storage and self-contained diesel heater for regeneration. This refrigerator is the subject of this report.

This report documents the design and testing of a field refrigerator that has been delivered to the U.S. Army Natick R&D center. The refrigerator is intended as a possible replacement for the ice box currently used in the Mobile Kitchen Trailer (MKT). The field refrigerator provides refrigeration with no continuous power input. Periodic recharging is required. Recharging is powered by a diesel-fired heater self contained with the refrigerator. Refrigeration capacity for up to two days of unattended operation is provided, but it is recommended that it be recharged daily to ensure that adequate charge is always available.

Charging is manually initiated by depressing a single button, and is fully automatic after that. Recharging takes 1 hour and 15 minutes, and will terminate automatically and return the refrigeration to cooling mode. Electrical power is required during recharging. Power required is 28 vdc, with 200 W draw at the start of the recharge cycle.

The refrigerator has automatic temperature control of the cold space. No electrical power is required when the refrigerator is not being recharged.

This simple user-friendly refrigerator should provide effective replacement for ice boxes in the MKT, and can eliminate the need to supply ice to the battle field.

[1] The original contract called for development of a 30 ft^3 hot-oil powered refrigerator during Phases III and IV.

PRINCIPLES OF OPERATION

The chill storage refrigerator developed under this contract utilizes a solid absorbent material to draw refrigerant vapor (ammonia) from the evaporator to produce cooling. When the absorbent is saturated with refrigerant, it is heated to drive refrigerant vapor to the condenser, to ready the system for another cycle of refrigeration.

Absorbents are materials which absorb a gaseous media at a pressure lower than the condensing pressure of the gas. When the gas is a useful refrigerant, sorbants can draw vapor from a low temperature and low pressure evaporator, thereby producing cooling. Once a sorbent is saturated, however, it must be regenerated to restore its absorption capacity. Regeneration is typically accomplished by heating the sorbent and driving off the refrigerant, whence it is condensed and stored for the next absorption cycle.

A regenerated absorbent has latent stored cooling potential which can be exploited by admitting refrigerant to an evaporator which is in vapor communication with the sorbent. Because the absorption process is exothermic, heat must be rejected from the sorber to allow absorption to continue to saturation.

The chill storage system on the Natick Chill Storage Refrigerator (CSR) functions on this sorption principle, using a complex compound as the absorbent and ammonia as the refrigerant. As used herein, complex compounds are substances comprising a base material and a polar gas, with the gas attached to the parent material by coordinative covalent bonds. Practical materials for chill storage applications are metal halide salts; the material used in the CSR is $SrCl_2$. Ammonia is used as the polar refrigerant, and was selected because: (1) it has a high heat of vaporization (4 to 5 times that of most common refrigerants) thereby producing a significant amount of cooling per unit mass evaporated and absorbed, (2) has sufficiently high vapor pressure at operating evaporator temperatures to provide good absorption, (3) is a small molecule which impacts absorption potential, and (4) has low molecular weight. Complex compounds are ideal absorbents because they can absorb large amounts of refrigerant and provide absorption at low pressures. The coordinative covalent bond between salt and refrigerant atoms is based on electron displacement rather than electron sharing or electron transfer between orbitals. Thus the number of molecules coordinated (bonded) is not limited by oxidation number of the substances used. Typically one mole of salt can coordinate 6 or 8 moles of refrigerant. $SrCl_2$ functions over the coordination step from 1 to 8 moles of ammonia per mole of salt. On a mass basis, this yields refrigerant absorption equal to 75% of the salt mass. Vapor pressures of $SrCl_2$ and ammonia are plotted against temperature in Figure 1. At any temperature, vapor pressure of $SrCl_2$ is significantly below ammonia vapor pressure. This vapor pressure suppression is the feature that allows the sorbent to draw ammonia vapor from an evaporator at low temperature and pressure. Also of importance is the fact that the complex compound exhibits a single vapor pressure curve, with vapor pressure being only a function of temperature. This characteristic is called monovariance. Many

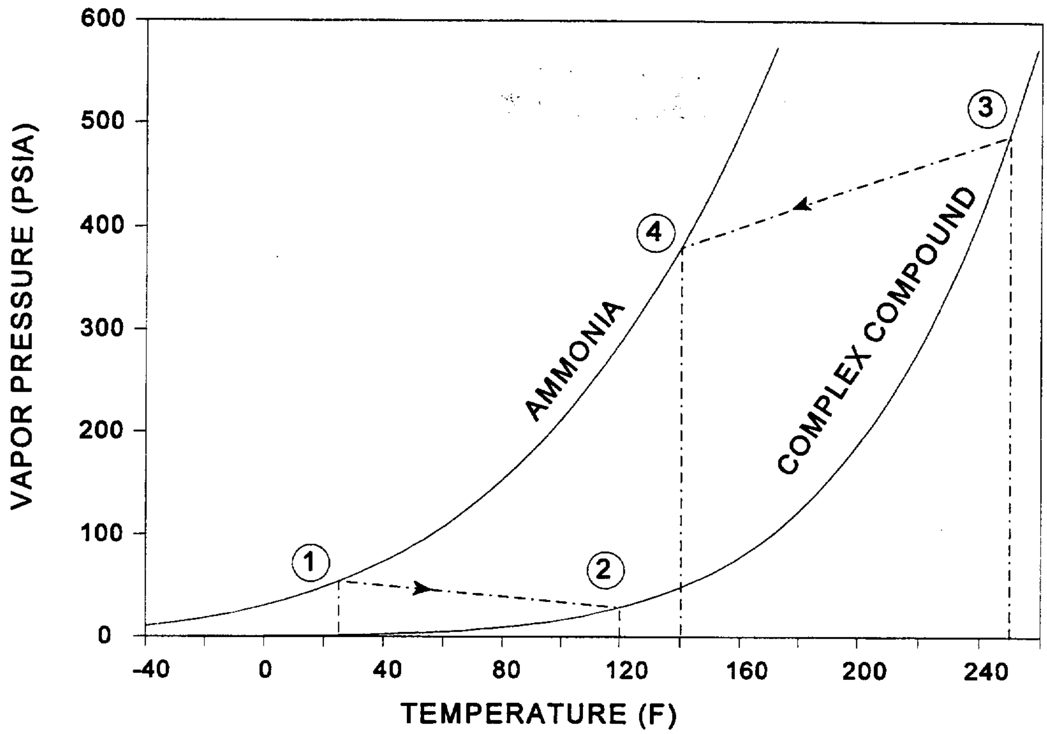

Figure 1.Vapor pressure of ammonia refrigerant and a complex compound absorbent.

sorbent materials are bivariant, meaning that vapor pressure depends on the amount of refrigerant absorbed as well as temperature. Vapor pressure of bivariant sorbents increases as refrigerant concentration increases. Monovariance is important for this chill storage application because required evaporator temperatures can be maintained for the entire sorption period; bivariant materials would exhibit increasing evaporator temperature and pressure as the sorption progressed. Monovariance also allows complete regeneration at a fixed sorber temperature.

During operation, evaporator temperature is approximately 25°F, as shown as state point 1 in Figure 1. At 25°F, evaporator pressure is above the complex compound pressure at 120°F (state point 2), and ammonia vapor can be drawn from the evaporator into the sorber. The sorber temperature is above ambient temperature because the absorption reaction is exothermic, and heat must be rejected to ambient. During this phase, system pressure is actually evaporator pressure, and the difference between evaporator pressure and equilibrium pressure of the complex compound provides temperature and pressure offset from equilibrium to drive the sorption reaction.

Regeneration is accomplished by heating the sorber sufficiently to raise complex compound pressure above condenser pressure. Figure 1 shows the complex compound heated to 250°F, (state point 3) for desorption against a condenser at

140°F, shown as state point 4. System pressure does not exceed condenser pressure during regeneration, and the difference between complex compound equilibrium pressure and condenser pressure provides driving potential for the desorption reaction.

Regeneration removes ammonia from the complex compound and creates the potential for the compound to absorb ammonia from the evaporator. Chill storage arises from the ability of the regenerated compound to absorb significant quantities of ammonia, thereby producing cooling at the evaporator. In actual operation, regeneration is accomplished in about an hour, and as sorbers cool the complex compound can absorb ammonia from the evaporator and provide cooling for 24 to 60 hours.

DESIGN

Requirements and Goals

1. Size: 6.3 ft^3 storage volume. Inside cold box dimensions 20"x21"x26"
   29 x 30" x 32 max outside (34 deep with stand)

2. Limit to 6.6 pounds ammonia total.

3. Smooth-wall evaporator integral with box liner.

4. Firing:

Espar diesel-fired fluid heater mounted on box	Preferred
Closed-loop boiler for new field burner	acceptable

5. Forced-convection condenser with DC fans

6. Thermostatic control of temperature of the refrigerated cavity.

7. 1-day operation in 115°F ambient. 40°F (4.4°C) box
   Should also comply with MIL-STD-210C (88 to 110°F ambient)
   and be operable in a Kuwait day (125°F for two hours)

8. Regenerate in 1 hour or less

9. Controls:
   a. Full-charge indicator
   b. Indicator to tell when charge is required
   c. Automatic regenerator shutdown on full charge
      -pumps off
      -fans off
      -burner (heater) off
   d. Automatic temperature control of fluid during regeneration
   e. Automatic box temperature control during discharge

10. Powered by 28 VDC.

System Design

Implementation of complex compound chill storage in hardware is straightforward. The most difficult challenge was developing a method for regeneration. Phase II utilized steam from a pressure cooker, with the pressure cooker being heated by an M2 Army field burner. The Phase II system is described in Appendix C. For the final TDP, a more passive approach to regeneration was desired, with fully automatic control. Use of a diesel-fired fluid heater was chosen. The fluid heater is a modified automotive engine preheater marketed in the U.S. by ESPAR, Inc.[2] The heater was modified to operate at 275°F fluid temperature, instead of the factory preset 180°F control point.

A flow schematic for the system is illustrated in Figure 2. Regeneration is achieved by heating the sorbers with a water-glycol mixture, which is heated by the ESPAR heater. As sorbers get hot and ammonia pressure is greater than condenser pressure, the check valve in the line between the sorber and condenser opens and ammonia flows to the condenser. After regeneration, as sorbers cool the discharge check valve opens and allows ammonia vapor flow from the evaporator to the sorbers. Routing of ammonia vapor to and from the sorber bank is accomplished passively with check valves.

The ESPAR heater system has fluid temperature controls, automatic shutoff, a fluid pump, expansion tank, and safety features. A separate section describes the ESPAR.

The refrigeration system includes a thermostatic expansion valve (TXV), and temperature control valve. The TXV controls refrigerant flow to the evaporator to maintain adequate refrigerant inventory in the evaporator while preventing evaporator flooding. The temperature control valve restricts ammonia. flow from the evaporator to the sorber when the box is cooled to the setpoint. Details on these components are included below.

Design and selection of components

Insulated box

The insulated box was selected to give roughly the same outside dimensions as the ice box currently used in the Mobile Kitchen Trailer (MKT), and to give increased storage volume considering that approximately half of the ice box is filled with ice. The MKT ice box is approximately 31 " high, 28.25" wide and 24.25" deep, with 2.25" wall thickness. Internal volume is 7.2 ft^3. The box is about 36.5" high overall including the skid on which it is mounted. Heat leakage is estimated to be 1.61 Btuh/°F, giving a design load (in 100°F average ambient and 35°F box temperature) of 2512 Btu/day.

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[2] ESPAR Inc. 17370 N. Laurel Park Dr Ste 400 E, Livonia MI 48152-9842.

Manufactured by J.Eberspächer, Ebersächerstr 24, D-73730 Esslingen, Germany.

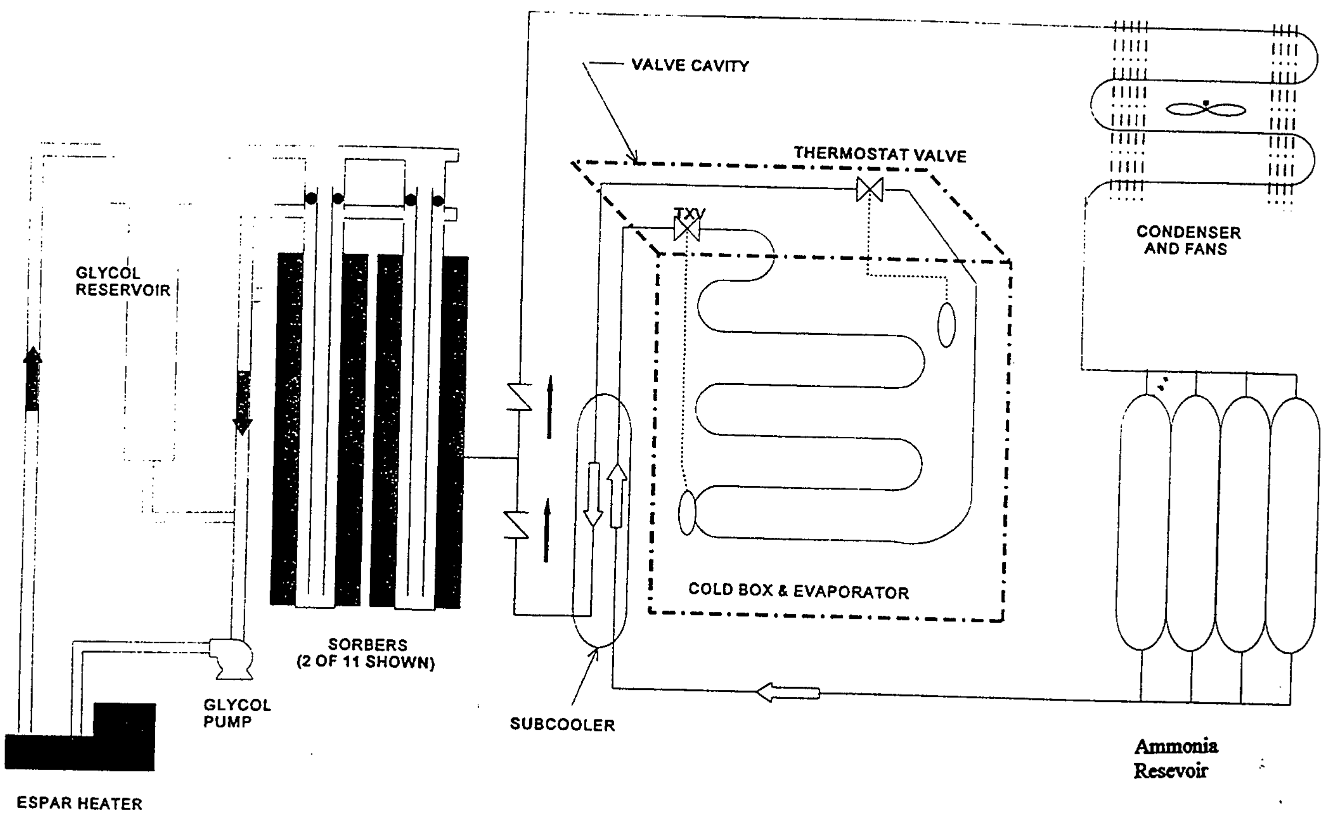

Figure 2. System Flow Schematic

The chill storage insulated box outside dimensions are 33" high, 27.5" wide, and 26.5" deep. Overall system dimensions, including the skid, are 32" x 30" x 35.25" tall. Inside dimensions are 20" x 21" x 26" deep. Storage volume is 6.3 ft^3. This is 88% of the original MKT ice box, which is half filled with ice, so usable volume is increased by about 2.7 ft^3. Wall thickness of the storage box is 3" and it is insulated with urethane foam with a k value of 0.015 Btu/hr-°F-ft. Heat loss is approximately 1.4 Btu/hr-°F, and daily heat leakage at 100°F average ambient temperature and 35°F box temperature is about 2200 Btu/day.

Sorbers

Sorbers consist of a finned volume in which solid sorbent is packed between fins, and a central heat transfer tube. An example sorber is illustrated in Figure 3. Sorbers cores for the chill storage box are fabricated from 3031 aluminum bar stock. Wolverine tube company extruded spiral fins from the surface of the bar, using the same method they use for making integral finned tube. The final product has a root diameter of approximately 0.815", an outside fin diameter of ≈1.615", fin thickness of 0.01", and 11 fins/inch. Sections of this finned stock 24" long are used for each sorber. These sorber cores were gun drilled with ½" diameter holes through the center of each core. A 3/16 tube is places inside the ½" diameter hole. Manifolding at the top of each sorber directs heated fluid down the central 3/16 tube, and fluid then flows up the annular space between the ½" hole and 3/16 tube.

The arrangement of 3/16 tube inside the ½ hole provided maximum heat transfer with minimum pressure drop. With an objective to minimize current draw from the 28 VDC system while providing adequate heat transfer for regeneration in approximately 1 hour, it is necessary to find a near optimum point in the pressure drop -heat transfer domain. The ESPAR heater requires fluid flow of at least 500 liter/hour (8.33 liter/minute, so this flow rate was used in calculations. It was found that with parallel flow through each sorber (0.76 liter/minute each) pressure drop of about 0.8' and heat transfer coefficients of about 600 Btu/hr-°F-ft^2 could be achieved. This heat transfer coefficient results in a temperature difference between heated fluid and the sorber wall temperature of 4.5°F. Heat transfer and pressure drop calculations were performed for a 50% mixture of ethylene glycol and water. Flow in the annular space is laminar or transition flow, depending on temperature. Reynolds number is 2100 at 200°F average fluid temperature, and 4600 at 250°F.

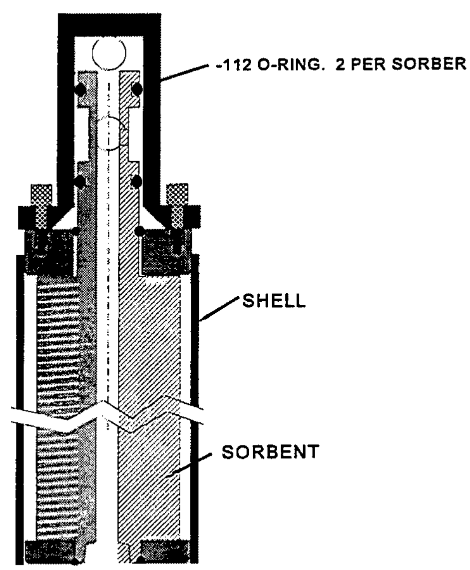

Figure 3. Sorber and glycol manifold assembly.

Sorber cores were placed in 6061 aluminum shells 2" OD and 0.083" wall thickness. End caps of 6061 aluminum were welded in place on each end to provide a pressure-tight system. Allowable stress for 6061 T6 aluminum tubes at 250°F is 12.1 ksi[3]. Required wall thickness for 400 psig pressure is 0.033", and stress at 0.083" wall is 4.8 ksi, well below allowable stress.

Each sorber holds 333 grams of salt. At a refrigerant uptake of 0.6 g/g, each sorber should provide 200 grams of ammonia for cooling the box. Eleven sorbers were used, giving a maximum ammonia uptake of 2200 grams, equivalent to approximately 2200 Btu of refrigeration. This equals the design load of 2200 Btu/day at 100°F average ambient.

The sorbers are inserted into the glycol manifold and fixed at the bottom to form a sorber bank assembly 22" wide and 28 ½ " high, by 2" deep. An ammonia vapor manifold at is welded to each sorber shell the center of the sorbers.

Sorbers for the CSR were built with Ryton (polyphenylene sulfide) felt wrapped around the finned section to hold salt between fins. The Ryton felt wrap fit tightly inside the sorber shells. The felt, backed up by the shells, provided a strong barrier to salt movement while being sufficiently permeable to allow ammonia vapor to pass through the felt and gain access to the salt in place of aramid.

In addition to absorption capacity, the ability of the sorbers to reject heat during absorption must be considered. Heat released during absorption is approximately 2.5 Btu/gram of ammonia. Each sorber with 333 grams of salt will absorb about 200 grams of ammonia, releasing 500 Btu of heat. Surface area of each sorber is 150 in^2 (1.05 ft^2), and the natural convection heat transfer coefficient will be about 0.61[4]. For a 24-hour absorption period, the heat rate is 21 Btu/hr, giving a temperature difference between the sorber and ambient of 33°F. Thus at 115°F ambient, the sorber shell temperature will be 148°F. Equilibrium pressure of the complex compound is 58.4 psia at 148°F, and ammonia evaporator temperature at 58.4 psia is 28°F. Thus the minimum evaporator temperature during operation at 115°F ambient will be ≈28°F.

Condenser

It is desired to limit condenser temperature to 146°F during regeneration in order to keep pressure below 400 psig. Thus at 115°F ambient, the allowed temperature difference between ambient and condenser is 31°F. Required heat rejection for regeneration in one hour is 2200 Btu/hr. The condenser selected is a Lytron 4121 which 9.7" wide by 5.8" high. With an airflow of 200 CFM this condenser is rated at 80

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3 Avallone and Baumeister (Eds), Marks' Standard Handbook for Mechanical Engineers, 9th Edition, New York: McGraw-Hill, 1986, pp 8-180.

4 Chapman, A. J., Heat Transfer, 2nd Edition, London: the Macillan Company, 1967, pp 366-367.

Btu/hr-°F itd. The coil is rated on the inlet temperature difference, which is condensing temperature minus inlet air temperature. So at 2200 Btu/hr and 200 CFM air flow, the coil will operate at 27.5°F above ambient temperature, which is acceptable.

Two F1238H12B Mechatronics 12 VDC fans are used to provide airflow through the condenser. These fans are rated at 112 CFM each, with 0.44 amp current draw.

Reservoir

Liquid ammonia must be stored in the system after regeneration, until it is evaporated and absorbed by the complex compound. A reservoir must be provided to store all ammonia desorbed. This storage capacity must be provided near the peak condenser temperature of 146°F. Ammonia liquid density at 146°F is 0.54 g/cc, so 4074 cc of reservoir volume are required to hold 2200 grams of ammonia.

The reservoir was constructed of 4 pieces of 2.5" OD by 0.083 wall aluminum tubing, each 17" long. This gives an internal volume of 4767 CC. Considerable over volume allowance is provided due to the severe consequences if the system becomes liquid full, and to allow adequate volume for desorption of more than 0.6 g/g ammonia from the sorbent, which is possible under certain conditions. Reservoir volume is adequate for desorption of 0.67 grams ammonia/gram sorber (6.2 moles ammonia/mole absorbent).

The reservoir material is 6061 T6 aluminum, with an ASME allowable stress of 12.7 ksi at 150°F[5]. Required wall thickness for 400 psig is 0.039", and stress with 0.083" wall is 6 ksi. Pressure rating for 0.083 wall is 844 psig.

Evaporator

The evaporator is part of the box liner. Aluminum tube is wrapped around the box and attached with epoxy, and tubing is also attached in a serpentine pattern on the bottom. Approximately 120 feet of 3/16 x 0.028" wall soft aluminum tube is used in the evaporator. The thermostatic expansion valve and thermostatic (temperature control valve) are both attached to the box liner. The TXV bulb is mounted with a plastic block which holds it against refrigerant tube in the position shown. Ammonia liquid is fed from the TXV to the top wrap of tubing.

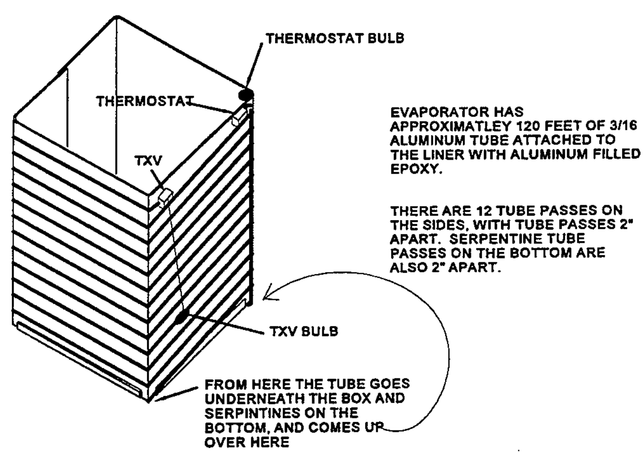


Figure 4. Evaporator and box liner.

5 Mark's Handbook, see reference 1.

Vaporizing ammonia progresses down the wall and then across the bottom, and finally directly up near one corner to the thermostat. Feeding ammonia to the top of the box tends to minimize temperature stratification.

Thermostatic expansion valve The thermostatic expansion valve (TXV) controls ammonia flow into the evaporator. The purpose of the TXV is to maintain sufficient ammonia in the evaporator to use most of the available heat transfer surface, while preventing the evaporator from flooding. Evaporator flooding is not desirable because it allows liquid ammonia to enter tubing outside the refrigerated box, where it evaporates and is absorbed by the salt--consuming some of the sorption capacity--without producing cooling inside the box. In extreme cases of evaporator flooding, liquid ammonia can reach the sorbers with potential for liquefying some of the salt, allowing it move inside the sorber, and permanently reducing the sorber effectiveness.

The TXV controls evaporator ammonia flow by sensing the temperature of the ammonia vapor at the TXV bulb position, and controlling the feed rate such that vapor is superheated by a fixed amount above saturation temperature. Superheat is typically controlled to 4°C to 8°C. Superheat control is achieved by using a bulb with a phase-change fluid to convert temperature to pressure. Bulb pressure is compared to refrigerant pressure at the TXV (evaporator inlet pressure) across a diaphragm. When bulb pressure is greater than evaporator pressure (plus a spring force), the superheat is too high, and the diaphragm opens the valve. When bulb pressure drops, indicating less superheat, the valve closes. The TXV used is a proprietary design developed at Rocky Research especially to control very low refrigerant flow rates. The valve appears to be very reliable; identical valves have been operating on sorption refrigerators and vapor compression refrigerators for 18 and 6 months, respectively.

The TXV bulb is positioned toward the bottom of the box, with about 75% of the evaporator tubing between the inlet and bulb, and 25% between the evaporator outlet and bulb. Theoretically the bulb should be placed at the evaporator outlet, but flooding can occur if bulb temperature change responds slower than changes in ammonia feed rate. Leaving some tubing between the bulb and evaporator outlet eliminates flooding due to response time.

The TXV is not intended to regulate box temperature, rather its only function is to keep the evaporator full of ammonia and operating at maximum effectiveness at all box temperatures.

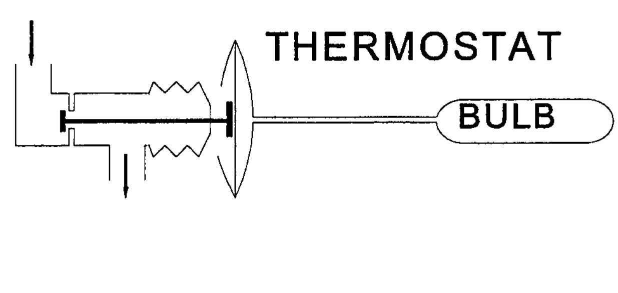


Figure 5. Thermostatic valve schematic.

Temperature control valve The function of the temperature control valve is control box temperature, and slow or stop absorption of ammonia vapor when the box temperature is at the set point. This is accomplished by restricting (and eventually closing) the vapor line between the evaporator and sorber bank.

The design of this valve--similar to the design of the TXV--is illustrated in Figure 5. The thermostatic valve is simply a diaphragm operated valve in which pressure in the bulb tends to open the valve. The valve is biased closed with a spring (not shown). The bulb is charged with butane, and bulb pressure increases as temperature goes up. The backside of the diaphragm is exposed to ambient pressure as a relatively constant reference pressure, and the valve stem is sealed with a bellows. The bulb is suspended inside the cold box, and senses box air temperature. When the bulb is warm, bulb pressure opens the valve and allows ammonia vapor to flow from the evaporator to the sorbers.

The bellows area is not insignificant compared to the diaphragm area, so the response of the valve is not independent of refrigeration system pressure. Thus valve setpoint is affected somewhat by ambient temperature because at elevated ambient both sorber pressure and evaporator pressure tend to rise. For most operating scenarios, however, it will not be necessary to readjust the thermostat. The unit is shipped with the thermostat set to control at about 35°F.

The temperature set point is adjusted using a thumbscrew which is only accessible when the refrigerator lid is opened. Turning to the right provides a colder setpoint. An arrow indicating direction for adjustment is adjacent to the thumbscrew.

The thumbscrew affects the valve setpoint by moving the diaphragm closer or further away from the bellows and valve body. The thumbscrew is attached to a threaded collar, which has threads with different pitch on the outside diameter and the inside diameter. The outside is threaded into the diaphragm housing, the the inside threads connect to the valve body. Turning the collar moves body and diaphragm relative to each other because of the difference in thread pitch between inside and outside threads.

Subcooler

The subcooler transfers heat from liquid ammonia flowing to the TXV, into cold vapor leaving the evaporator. This increases subcooling of liquid flashing through the TXV into the evaporator, thereby decreasing the vapor fraction as it flashes to evaporator pressure. Reduced vapor fraction provides more refrigeration per unit mass of refrigerant. Hence the functional objective of including the subcooler is to increase refrigeration capacity without increasing refrigerant mass or sorbent mass. Depending on ambient temperatures, capacity is increased by 5% to 10%.

The subcooler used on the CSR is simply a tube-in-tube heat exchanger. Liquid to the TXV flows through a 1/4" OD tube, which is inside a 3/8 OD (0.305" ID) tube. Vapor from the evaporator flows in the annual space inside the 3/8 tube around the 1/4" OD

tube. The length of the subcooler is 22".

Glycol Pump

A 12 vdc pump is provided to circulate glycol-water mixture through the ESPAR heater and sorber bank. The pump supplied with the ESPAR heater was not used because it was not rated for operation at 275°F, as required for this application.

A March[6] 809-PL-12 pump was used. This is 809-BR-12 pump with the bronze housing replaced with polysulfit plastic. The plastic housing is part number 809-079-10. The pump is 12 VDC with 1/100 HP motor, with rated current draw of 1.5 A. Rated flow at zero head is 3 GPM, and shutoff head is about 4 feet. The operating point in the system is approximately 2.2 GPM at 2' head.

[6]March Manufacturing, 1819 Pickwick Ave, Glenview IL 60025. (847) 729-5300

ESPAR DIESEL-FIRED HEATER

The system is recharged with hot coolant (glycol-water mixture) supplied by a modified Espar D4W hydronic heater. The heater runs on diesel fuel and has three power levels: boost (4 kW), high (3.3 kW), and low (1.6 kW). Operational control, including switching between power levels, is controlled by an electronic module which is part of the ESPAR heater system. This control module performs numerous checks on operation to ensure safety and reliability of the ESPAR heater. Functions performed by the ESPAR control unit include:

1. Control of coolant temperature by changing power levels and on/off operation.
2. Safety shutdown for coolant over temperature
3. Control of startup, running, and shutdown phases
4. Monitoring of blower speed, flame sensor, and fuel pump faults
5. Control of attempted restart following fault(s)
6. Shutdown after 3 failed restarts

Al fault-code retrieval unit allows determination of the fault sensed by the control unit. The ESPAR manual[7] contains a listing of fault codes.

The ESPAR D4W is designed to provide auxiliary heat for motor vehicles and originally ran at a maximum temperature of 185°F. Several modifications were necessary to increase the maximum temperature to 266°F, as required to recharge the field refrigerator. The built-in water pump was replaced with a separate pump designed for the higher temperature. Likewise, the integral electronic control unit was removed and located remotely to avoid overheating of the electronics. The control unit has no provisions for modification or adjustment so the temperature sensors were changed to obtain the higher temperature. The control temperature and over temperature sensors were replaced with 50 kΩ thermistors, which have about the same resistance and temperature coefficient at 266°F as the original 10 kΩ thermistors at 185°F. While the heater ran fine with this change, it would not restart when hot, with the control unit returning the fault code for "faulty flame recognition," i.e. the flame sensor indicated high temperature with no flame present. A 16.2 kΩ resistor wired in parallel with the 1000 Ω RTD flame sensor resolved this problem.

During operation, the heater goes through startup, running, and shutdown phases. These phases are illustrated in Figure 6.

[7] File *dw4.pdf*, included with this report. Requires Adobe Acrobat reader.

	STARTING PHASE					RUNNING PHASE	SHUT DOWN PHASE		
OPERATING MODE	SYSTEM CHECK	Pre-Heat	Ignition Attempt	Pre-Heat 2nd attempt	Ignition attempt (2nd try)	* Controlled Heating	After Glow	Cool Down	OFF or Stand by
water pump	Off	On	On	On	On	On	On	On	Off [On if in stand by]
Blower	On momentarily	Off	On	Off	On	On	On	On	Off
Glow pin	Off	On	On	On	On	Off	On	Off	Off
Fuel pump	Off	Off	On	Off	On	On	Off	Off	Off
TIME	1-3 sec	80 sec	up to 90 sec	80 sec	up to 90 sec if required	High/low Operation until switched off manually or automatically	20 sec	2.5 min	

* Note: During the controlled heating cycle, if the coolant temperature exceeds 266°F the heater will cycle off. Heater will automatically restart in high mode once coolant temperature reaches 221°F.

Figure 6. Espar Heater Operational Flow Chart

Startup

A system check is performed for a few seconds and the combustion air blower is turned on momentarily. The water pump and glow plug are turned on and pre-heat occurs for 80 seconds. Ignition is then attempted for 90 seconds, as the fuel pump and combustion blower start and gradually increase in speed. If ignition does not occur, the preheat/ignition sequence is repeated and if ignition does not occur on the second attempt, the heater will enter the shutdown phase and the control unit will return the fault code for "no start safety time exceeded".

Running

If ignition is successful, the glow plug is turned off and the heater gradually increases the high power level, holds for a few seconds, then increases to the boost power level. The heater returns to high power when the coolant temperature reaches 212°F and enters low power at 257°F. It then cycles between low and high power to maintain temperature. If the load on the heater is insufficient and the temperature continues to rise while in low power mode, it will shut down at 266°F and remain on standby until the temperature falls to 240°F, at which point the startup is repeated.

Shutdown

Afterglow: the fuel pump is turned off and the glow plug is turned on for 20 seconds.
Cooldown: the combustion blower and water pump remain on for 2.5 minutes.
IMPORTANT: Do not interrupt the 28 VDC electric power while the heater is running. If it is necessary to remove electric power, use the "abort recharge" button and wait until the green "recharging" indicator light goes out. This indicates that the normal shutdown cycle is complete. As soon as the button is pressed combustion will cease, but condenser fans and water pump will remain on until the shutdown is complete.

ELECTRICAL DESIGN

Control and monitoring of the ESPAR heater is performed by the electronic module provided with the ESPAR heater, modified for high-temperature operation as described above. Electrical components, controls and indicators--in addition to the ESPAR control module--are provided for the following functions:

1. Lamps and sensors to indicate the status of recharge or discharge, as represented by ammonia level in the reservoirs. Low-level and high-level indicators are provided. Low-level alerts the user that recharge should be started in the next several hours, and high-level tells the operator that the reservoir is full.

2. A lamp to indicate when recharge is in progress

3. A lamp to indicate when power is attached

4. Circuits to signal the ESPAR module to startup through its normal Startup-running-shutdown sequence when the operator presses the "Recharge" button.

5. Circuits to signal the ESPAR module to enter normal shutdown phases when recharge is complete. Complete recharge is indicated by either time out of the timer relay (75 minutes) or a high-level signal from the high-level sensor.

6. Circuits to abort recharge while allowing the ESPAR to execute normal shutdown phases.

7. A DC-DC converter to power electrical components (all of which are 12 VDC) with the military-standard 28 VDC power source.

Operating sequence

The wiring diagram for the CSR is shown in Figure 7. Connectors B1 and B2 interface with the ESPAR control module. Wiring and logic within the control module are not shown.

Connecting 28 VDC power to the CSR illuminates the power lamp, provided the 28 VDC to 12 VDC converter is operational, and both the 10A 28 VDC and 15 A 12 VDC fuses are conducting. As soon as power is applied, the low-level sensor will indicate if liquid ammonia in the reservoir is above or below the sensor level. Connecting power also powers the ESPAR daignostic unit and the ESPAR control module (pin 1 on connector B1) but does not give the ESPAR a start signal.

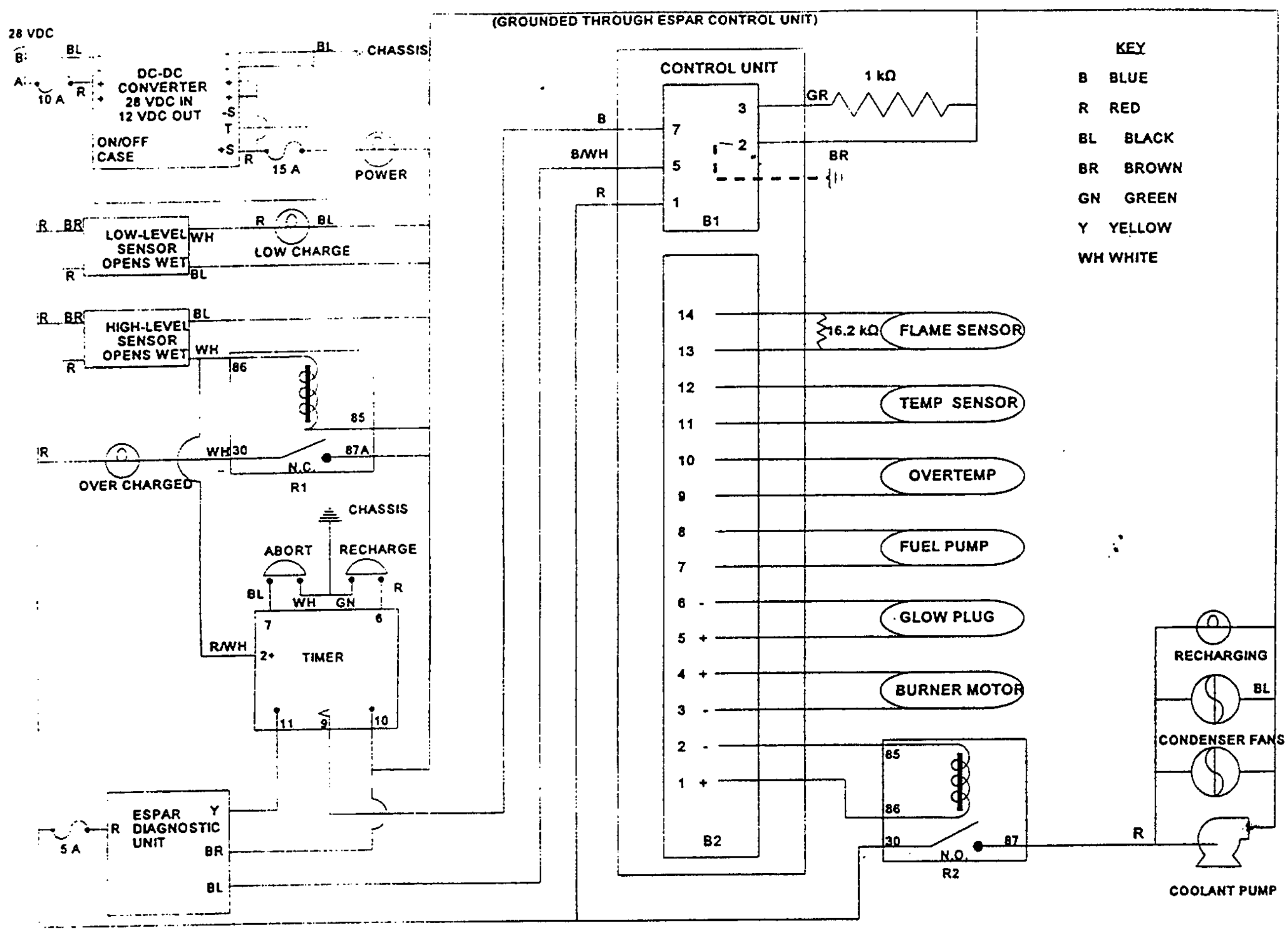


Figure 7. CSR Wiring Diagram

When the user initiates recharge by pressing the momentary contact switch, the timing relay is activated and begins a 75 minute countdown. The timing relay closes contacts between pin 9 and 11, thereby putting power to pin 7 of connector B1, which signals the ESPAR to start. Closure of contact 9 to 11 also powers the recharging indicator lamp.

The timing relay is powered at pin 2 (+) and 10 (-). Thus is the high-level indicator is open (indicating high level) at the start of the recharge cycle, or if it opens during recharge, power is removed from the timing relay and the contact between pins 9 and 11 is broken. Loss of voltage on pin 7 (B1) causes the ESPAR to go into the normal shutdown sequence.

Recharge will normally be terminated by time out, rather than high level indication. High level alone cannot be used to terminate recharge because ammonia liquid density varies considerably with temperature, and setting a high-level cutout for one tempeature will significantly prematurely terminate recharge when liquid temperature is higher. For this design, the high-level point is suitable for the highest expected liquid temperature, and this level will not be reached at most temperatures. Thus normally recharge is terminated by time out of the relay, and the high level sensor provides backup safety to ensure the reservoir never becomes liquid full.

This discussion of operating sequence illustrates the function of most electrical components. A few additional points are:

1. The third connection on the ESPAR diagnostic unit (BI to pin 1 at B1) returns fault codes from the control module.

2. The 1 kΩ resistor from pin 3 of connector B1 to ground simulates the load of a relay provided with the original ESPAR, whose function was to control fans in the car. The ESPAR control module will not function without this electrical load.

3. Relay R1 "reverses" the signal from the high level sensor, so that when the sensor contacts open indicating high level, relay R1 closes and energizes the high-level indicator lamp.

4. Relay R2 is energized by the ESPAR control module, and applies power to the condenser fans and pump. This relay is used to avoid excessive electrical load on the ESPAR module.

Components

Electrical/electronic components used for monitoring and control of the CSR include:

Level Sensors	Omega LVU-700 Ultrasonic Point Level Switch 1 A contact @ 12 VDc power 6.2 mA idle and 37 mA relay on @ 12 VDC
Timing relay	Siemens digital time delay relay/counter model CNT-35-26 12VDC 10 A relay contact power 70 mA idle, 70 mA relay on @ 12 VDC
Relays R1 & R2	12 VDC/30A automotive blower relay 90 Ω coil, 133 mA holding current @12 VDC
LO, HI, Heater LEDs	20 mA @ 12VDC 600 Ω (Built-in 500 Ω in series with LED)
Illuminated Switch	30 A contact @ 12 VDC power for light 60 mA
DC to DC converter	International Power Devices (IPD) Model XWS2413-HS/C 18-36 vdc in,12 vdc/15 amp out B.J. Wolfe Co, CA; (818) 889-8412

System Current

Measured current draw of the DC-DC converter for different operating modes are:

Peak draw	6.9 A @ 27.5 VDC (during glow plug on)
Hi Power mode	3.3 A @ 27.8 VDC
Medium power	2.6 A @ 27.8 VDC
Low power	2.1 A @ 27.9 VDC
Idle	0.27 A @ 28.06 VDC (heater off)

Test Ports

Test ports are provided for troubleshooting if necessary. Resistances and voltages measured prior to shipping the unit to Natick were:

Test ports	Item	Ohms disconnected	Voltages (System running)
14, 13	Flame Sensor	0.78k	≈2.0 @ 240°F coolant
12, 11	Temp Sensor	5k	≈1.2 @ 240°F coolant
10, 9	Over Temp	5.13k	≈1.4 @ 240°F coolant
8, 7	Fuel pump	9.7	-0.5 to -1.0 (bouncing analog meter)
6-, 5+	Glow Plug	1	5.91 (starts) 0.131 (off)
4+, 3-	Burner motor	3.7	8.35 high 6.52 medium 3.6 low
2-, 1+	Fan/H_20 Relay	86.3	12.88

OPERATING RESULTS

Tests of the CSR TDP at Rocky Research were performed in various ambient temperatures or ambient temperature profiles. Testing was also done starting with a warm box, as well as starting with a cold box and regenerating while some refrigeration capacity remained. Table I is a matrix of test conditions, and identifies figure numbers and data files for tests at different conditions.

Table 1. Matrix of test conditions for CSR testing at Rocky Research

	WARM BOX	COLD BOX
NORMAL AMBIENT	Figure 8 File NAT118B (46 hours, refrigeration only) Figure 9 File NAT1202 D (Only 1st 20 hours relevant)	Figure 10 File NAT1221E
CONSTANT-TEMPERATURE HOT AMBIENT	Figure 11 NAT1125A (Recharge only)	
KUWAIT DAY		Fig 12 Files 1214 + 1215A

Normal Ambient with a Warm Box

Refrigeration performance in normal ambient temperature (≈70°F) is shown in Figure 6. (The recharge part of this run is not shown because it was performed when times were still being adjusted, and includes manual restarts.) This is the only test where the box was allowed to run to full discharge in normal ambient. Box temperature stayed below 40°F for over 46 hours. Box temperatures were measured in three locations, top middle, and bottom. A 3/8 OD copper tube 37.75 inch long was placed diagonally in the refrigerated chamber, and thermocouples attached to this copper tube at the center and 1" from each end, to indicate box temperature at 3 locations. As revealed in Figure 8, very little variation in temperature between locations is observed.

Also plotted in Figure 8 are refrigerant temperatures at the evaporator inlet (just afterthe TXV), at the evaporator outlet, thermostat valve outlet, and the thermostat bulb.

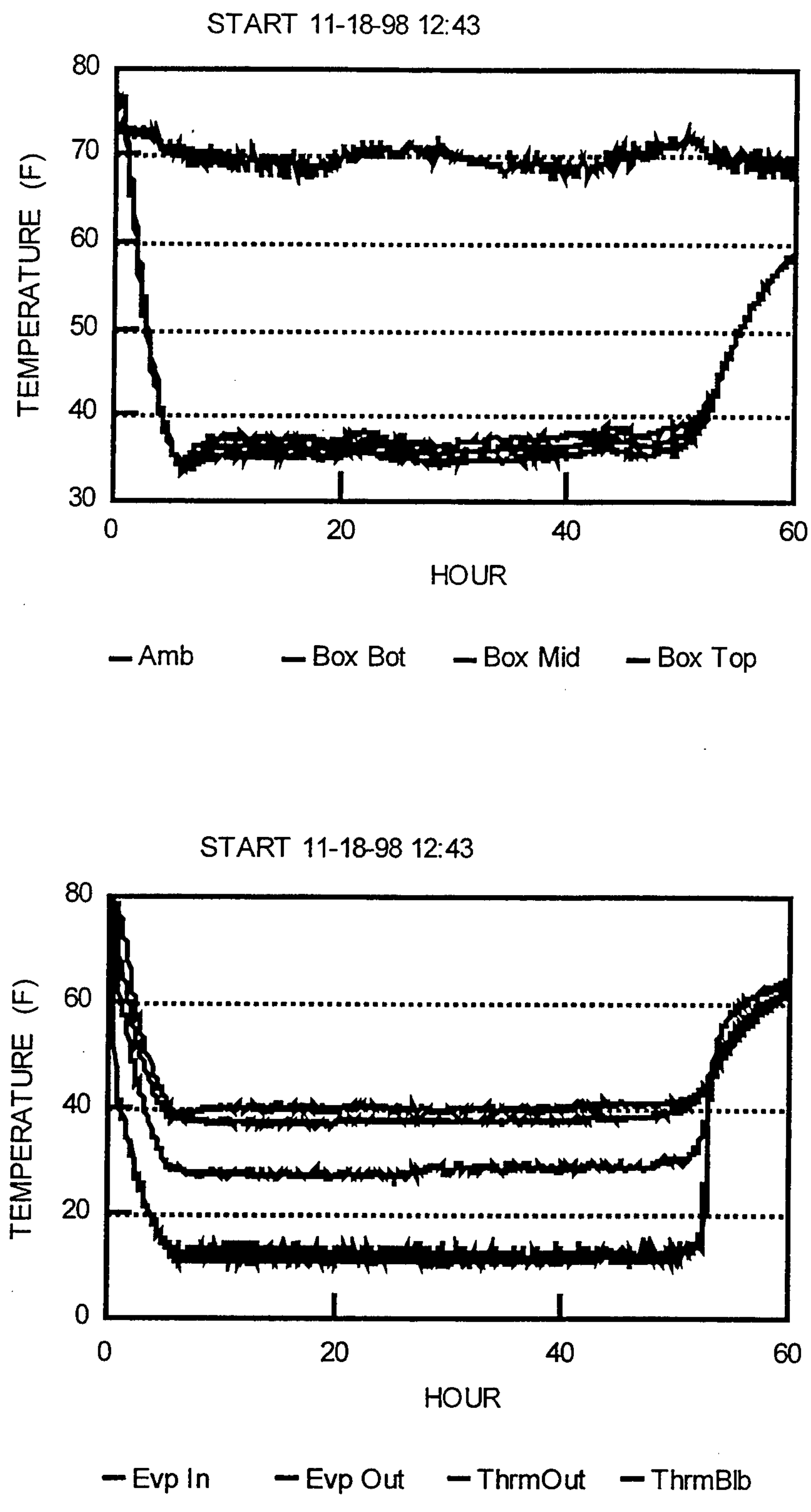


Figure 8. Refrigeration in normal ambient, starting with a warm box.

These data show nearly 20°F superheat (difference between evaporator inlet and outlet temperatures) which is higher than necessary. Excessive superheat results in low evaporator pressure, and slower absorption rates. Superheat was adjusted lower by decreasing spring force in the TXV after these data were taken. Ammonia vapor temperature leaving the thermostat valve, and the temperature of the bulb, are nearly equal to box temperature. This is typical for most runs. Themostat bulb temperature is the control point and is supposed to be close to average box temperature.

Figure 9 shows a recharge and partial discharge in normal ambient temperature. Following the 24 hour time window plotted, a recharge was attempted and terminated due to a leak in the glycol circuit. Data plotted show behavior of various temperature points during recharge in a normal ambient temperature. The lower plot in the figure is an expanded view of the first two hours, showing relevant temperatures during recharge. Glycol temperatures into and out of the sorber bank (Clnt in & Clnt out) are shown, together with the shell temperature of sorbers at the top and bottom. Also shown are temperatures of ammonia vapor entering the condenser, and ammonia liquid leaving the condenser and flowing into the reservoir. Condenser out temperature is an approximate indication of saturation temperature, although there is some subcooling of the liquid at this point.

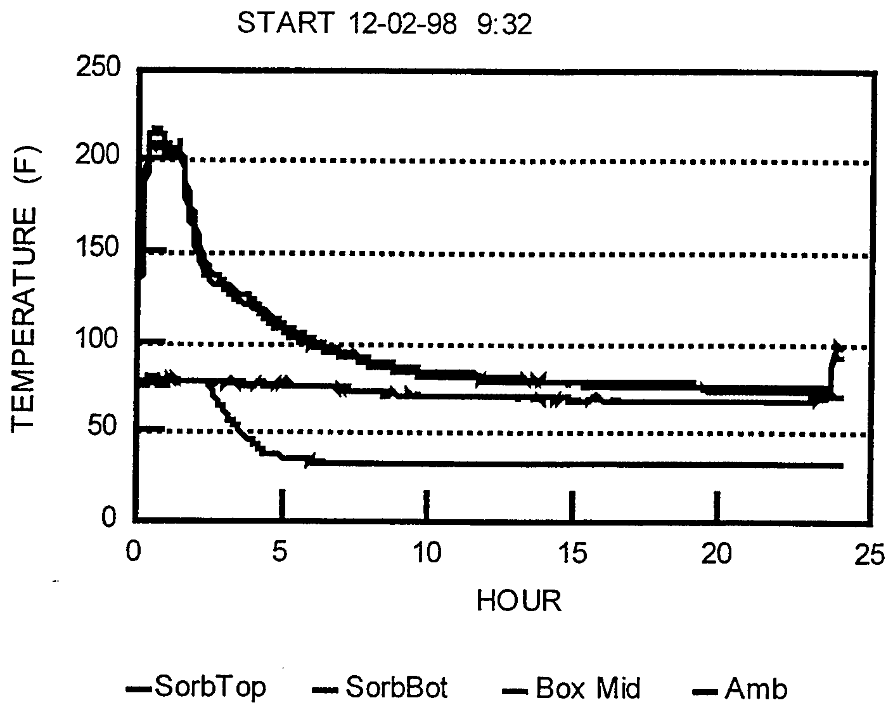
The ESPAR heater starts at boost power level (4 kW) and switches to high power (3.3 kW) at 212°F. Operating temperature of 250°F is maintained by automatic switching between high and low (1.6 kW) power. When recharge is complete the load on the heater decreases and temperature continues to rise with the low power setting. At 266°F the heater shuts off. The temperature rise is obvious in Figure 9; from about 1.25 to 1.5 hours glycol temperatre increases steadily.

Normal Ambient with a Cold Box

Recharge and cooling performance in laboratory ambient temperatures, with recharge initiated while the cabinet is cold and before complete discharge, is documented in Figure 10. The first plot (upper left) shows cabinet temperatures. These increase to 50°F during recharge because no refrigeration can be peformed during recharge. These data are taken with an empty box. The increase to 50°F would be considerably less with cold product in the box, which would add thermal inertia.

Process temperatures during recharge are shown in the upper right plot. It can be seen that temperature control to 250°F is achieved, and recharge is terminated on time out at 1.25 hours, eliminating temperature spiking at the end of the recharge cycle.

Evaporator inlet and outlet temperatures are plotted in the bottom charts of Figure 10, as well as caluculated superheat (evaporator outlet temperature minus evaporator inlet



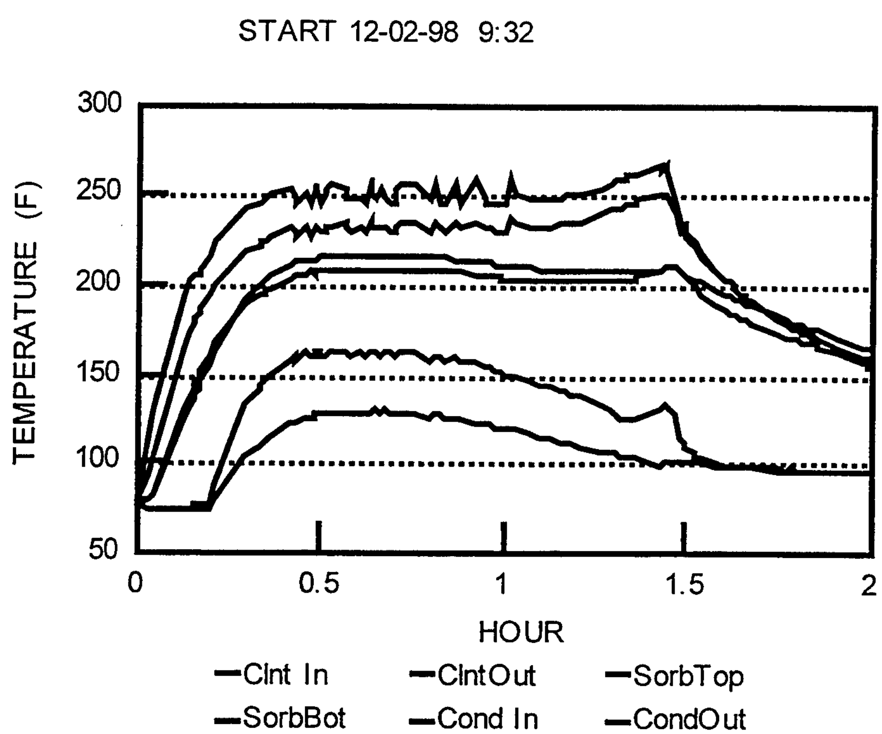


Figure 9. Recharge and discharge in normal ambient, beginning with a warm box.

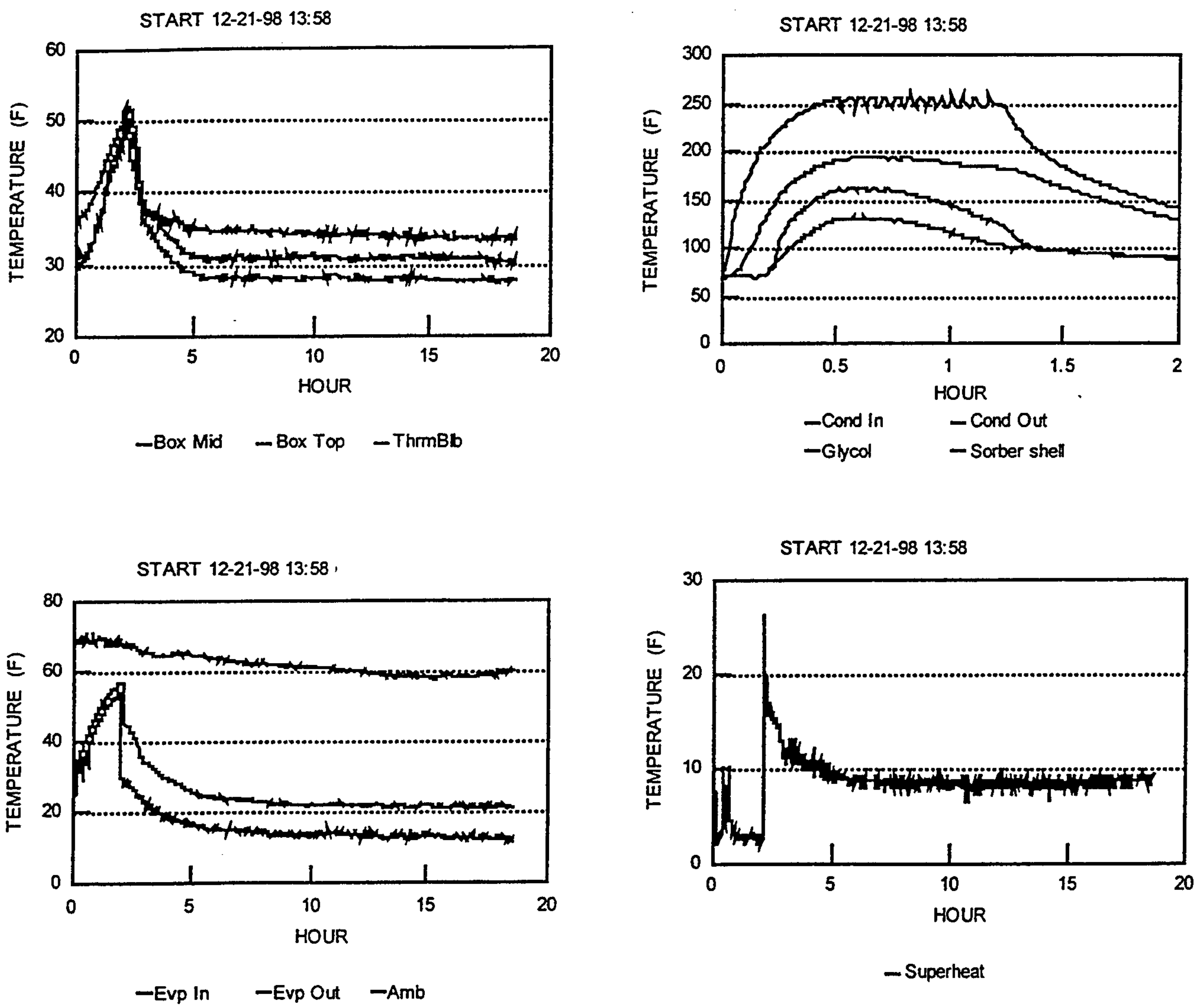


Figure 10. CSR performance in normal ambient, starting with a cold box.

temperature). Superheat of about 9°F is obtained. This is the lowest practical superheat setting. Lower superheat can be maintained during steady state operation, but evaporator flooding will occur during transients if lower steady-state superheat is attempted.

Constant-Temperature Elevated Ambient with Cold Box

No complete runs were made at constant temperature elevated ambient. Recharge in 100°F ambient is plotted in Figure 11. Performance is similar to recharge at normal ambient except temperature of ammonia into and out of the condenser is higher. These data were taken before the recharge timer was set to 1.25 hour. In this run, the ESPAR heat was on for 1.5 hours, but recharge was actually completed much earlier. Completion of recharge is indicated by condenser temperatures approaching ambient

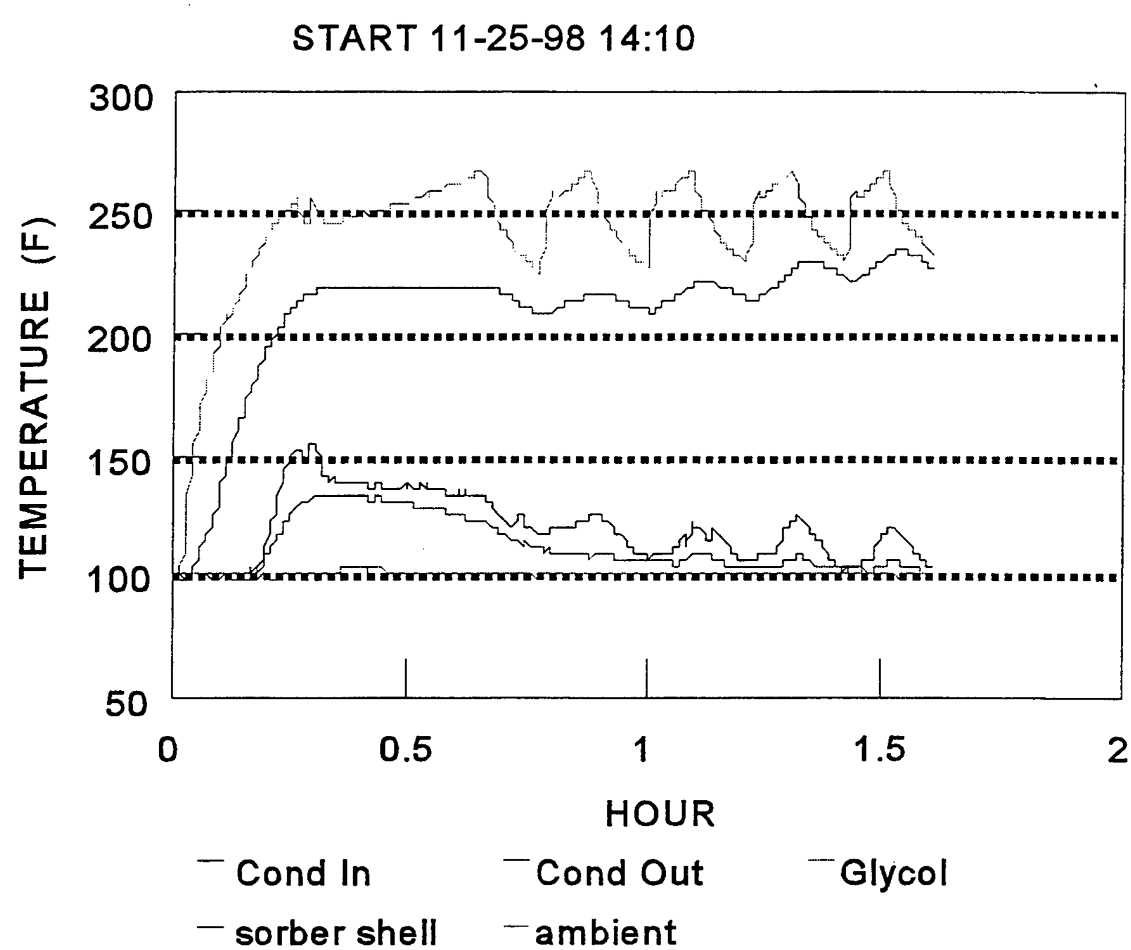


Figure 11. Recharge in 100°F ambient.

temperature at about 1 hour into the run.

Kuwait Day

Recharge and cooling tests were run in a temperature profile intended to be representative of a diurnal cycle in Kuwait. The temperature cycle--obtained from Natick--is:

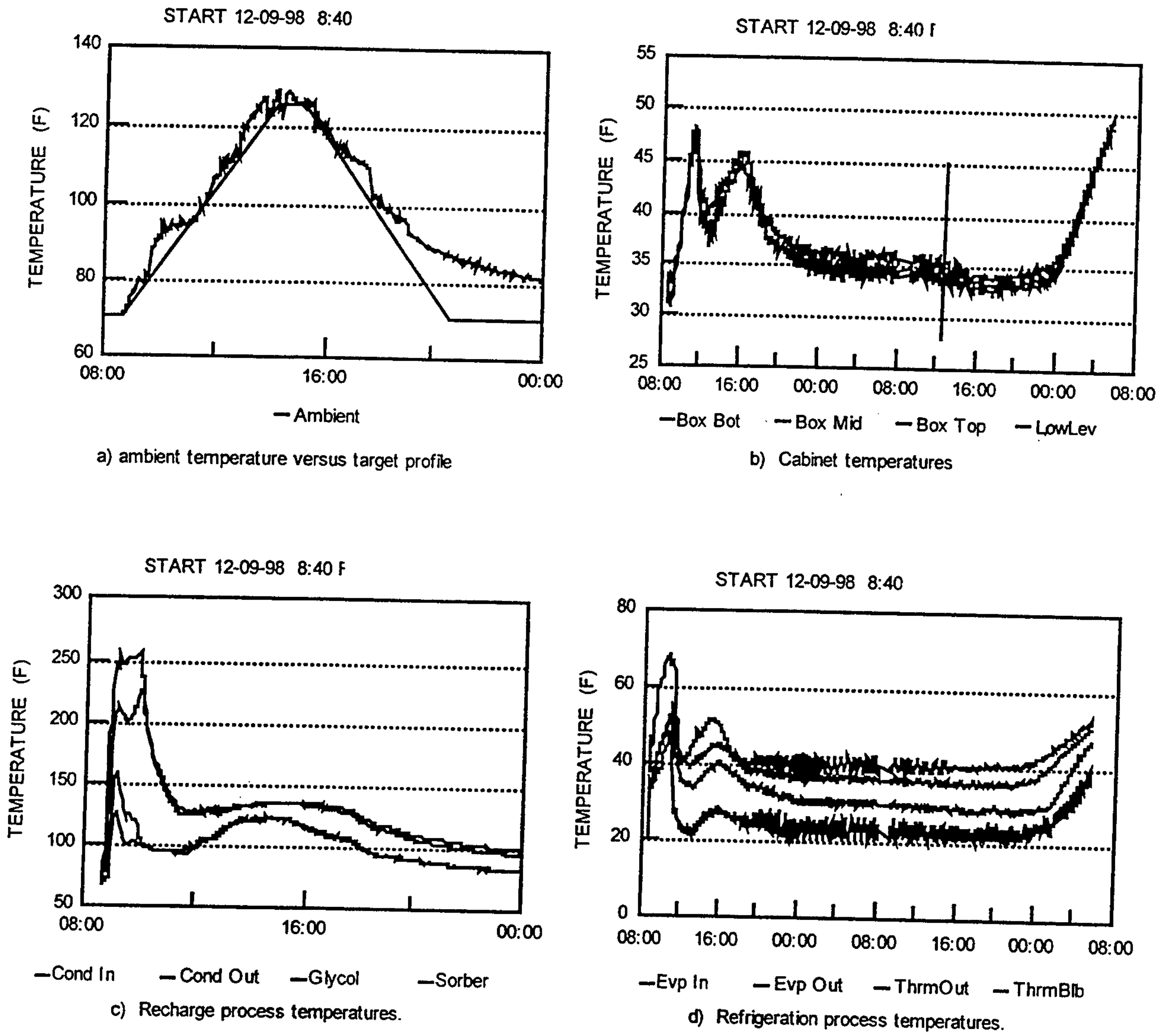
06:00 to 11:30	Temperature increase from 70°F to 125°F @ 10°F/hour.
11:30 to 12:30	Constant 125°F
13:30 to 18:00	Temperature decrease to 70°F at 10°F/hour
18:00 to 06:00	Constant 70°F

Tests were conducted with a cold box, with recharge starting at the same time as the ramp up in temperature at 10°F /hour.

Figure 12 shows performance of the CSR during a Kuwait day temperature cycle. Recharge and temperature ramp up to 125°F both began at 08:40 in this test. Figure 12a shows the temperature-time profile obtained over the first 16 hours, and the desired profile. The desired profile matched reasonably close except for cooling ambient back to 70°F was slower, and 70°F was actually never reached.

Temperatures inside the CSR are plotted in Figure 12b. During regeneration, temperature in the refrigerated space reached 47°F, and cooled back to about 37°F after regeneration was complete. However, as ambient climbed toward 125°F, box temperature increased again to about 46°F. The CSR basically has very little cooling capacity at 125°F, and for the two hours or so when ambient is above ≈120°F, thermal inertia of the box contents must be relied upon to keep them cold.

Also shown in Figure 12b is the time at which the low-level sensor tripped. The sensor tripped at about 12:00 on the second day, but significant box warming, indicating charge depletion, did not occur until about 12 hours later. Thus in normal (≈70°F) ambient, about 12 hours of refrigeration is available after the low-level light comes on. This time period will be shorter at higher ambient temperatures.



a) ambient temperature versus target profile

b) Cabinet temperatures

c) Recharge process temperatures.

d) Refrigeration process temperatures.

Figure 12. CSR performance with Kuwait-day temperature profile starting with a cold box.

Process temperatures during recharge for the Kuwait day temperature cycle are plotted in Figure 12c. These temperatures are shown for the first 16 hours. Sorber and glycol temperatures during recharge are similar to results of tests at other conditions. Condenser temperatures are also similar because regeneration is complete early in the temperature ramp when ambient is still not excessive. After recharge is complete, condenser temperature tracks ambient temperature fairly close, and sorber temperature remains about 10°F above ambient, since heat is being rejected from the sorbers to ambient. At 135°F sorber shell temperature, salt temperature is probably at least 140°F, and probably higher. At 140°F, equilibrium pressure of the salt-ammonia complex is 3.3 bar. Ammonia evaporating temperature at 3.3 bar is 19°F, but absorption rates would be zero with a 3.3 bar evaporator. Evaporator temperature must be at least 10°F higher to get meaningful evaporator rates and cooling capacity.

Evaporator and ammonia vapor temperatures are plotted in Figure 12d. At about 16:00 hours, when ambient is near maximum and sorber shell temperature is 140°F, evaporator inlet temperature increased to 27°F. At 27°F, ammonia vapor pressure is 3.8 bar, only ½ bar above salt equilibrium pressure of 3.3 bar. Approach pressure of at least 1 bar is required for reasonable absorption rates. Low rates and low cooling capacity are expected at an ambient temperature of 125°F.

SAFETY

Safety issues which must be adequately addressed in design and operation of the Chill Storage Refrigerator (CSR) are (1) use of ammonia refrigerant, (2) use of diesel fuel combusted in the ESPAR heater, and (3) use of pressurized water-glycol at about 20 psig.

Standards Compliance

Ammonia Refrigerant

The CSR utilizes ammonia refrigerant which represents the most important safety concern with the device. Ammonia, designated refrigerant 717, is classified as a Safety Code Group B2 refrigerant by Standard ANSI/ASHRAE 34[8]. The letter designation refers to toxicity, with "A" being lower toxicity and "B" being higher. Only letters "A" and "B" are used by ASHRAE. Class B refrigerants are those "...for which there is evidence of toxicity at concentrations below 400 ppm, based on data used to determine TLV-TWA or consistent indices." The number designation (ranging from 1 to 3) refers to flammability, with 1 being no flame propagation, and 3 being highest flammability. Class 2, per ASHRAE 34, signifies refrigerants with lower flammability limit of more than 0.00625 lb/ft^3, and a heat of combustion less than 8,174 Btu/lb. Ammonia is flammable in air in concentrations of 16 to 25 % by volume.

Ammonia is classified as a group 2 gas by Underwriters Laboratories report MH-2375. Underwriters Group 2 classification is for "Gases or vapors which in concentrations of about ½ to 1 percent for durations of exposure of about ½ hour are lethal or produce serious injury."[9] UL classification includes groups 1 to 6, with 6 being least hazardous and 1 being the most hazardous.

Standard ANSI/ASHRAE 15-1994, "Safety Code for Mechanical Refrigeration"[10] is the dominant authority for design and application of refrigeration systems. ASHRAE 15 allows use of up to 6.6 pounds of ammonia refrigerant in all occupancy classifications except Institutional[11], provided the following conditions are met:

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8 ASHRAE Standard ANSI/ASHRAE 34-1992, Number Designation and Safety Classification of Refrigerants, American Society of Heating and Refrigerating Engineers, 1791 Tullie Circle, Atlanta GA. Phone (404) 636-8400.

9 1989 ASHRAE Handbook, Fundamentals, American Society of Heating and Refrigerating Engineers, 1791 Tullie Circle, Atlanta, GA.

10 ASHRAE Standard ANSI/ASHRAE 15-1994, Safety Code for Mechanical Refrigeration, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, NE, Atlanta, GA.

11 Institutional Occupancy is defined by ASHRAE 15 as premises housing "disabled, debilitated, or confined..." occupants, and is not relevant to the MKT application.

1. The area is ventilated

2. The area is not a public hallway, or lobby

3. The refrigeration system is a sealed absorption system; for residential and commercial occupancies, the sealed absorption system limitation does not apply.

The CSR contains 6.6 pounds of ammonia and meets all of these conditions, so code compliance is assured for up to 6.6 pounds of ammonia. The system contains 8.75 pounds of salt ($SrCl_2$), and is typically charged by allowing the salt to absorb ammonia vapor with no liquid present in the system. The charge limit of 6.6 pounds of ammonia corresponds to 7.0 moles of ammonia per mole of salt. This salt has a theoretical uptake of 8.0 moles/mole, but uptake beyond 7.0 or 7.2 is too slow for practical use in producing refrigeration. However, it must be noted that the system is capable of absorbing more ammonia than 6.6 pounds, and for ASHRAE 15 compliance, ammonia charge should always be weighed in.

Design Pressures

The CSR is designed to minimize the possibility of ammonia leakage due to pressure vessel rupture. ASHRAE 15 requires a design pressure corresponding to saturation pressure at 122°F. The CSR was designed for saturation pressure of ammonia at 146°F, which is 400 psig. This design temperature was based on condenser capacity when being regenerated in 115°F ambient.

Sorbers and reservoir tubes are the largest diameter components in the CSR, and the ratio of diameter to wall thickness makes these the weakest components for pressure holding capability. Thus design pressures for these components are limiting.

Sorbers

Sorbers are 6061 Aluminum with 0.083 wall thickness and 2" outside diameter. Stress at 400 psig design pressure is 4.8 KSI. Allowable stress, which includes a significant safety factor, of 6061 at 250°F is 12.1 KSI[12], 2.5 times actual stress at design pressure. Tensile strength of 6061 Aluminum at 300°F is 45 KSI, 9.4 times design stress.

ASHRAE 15 requires that pressure vessels less than 6 inch inside diameter be protected by a pressure relief devices or fusible plugs. The CSR has no pressure relief valves, but is protected with a fusible plug. There is no isolatable section that is not in communication with the fusible plug, unless there are multiple faults such as check valves being stuck closed. The fusible material is trade named Cerroshield[13] and has a fixed melting point of 203°F. Composition is 52.5% Bi, 32% Pb, and 15.5% Sn.

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[12] Mark's Standard Handbook for Mechanical Engineers, 9th edition, p 8-181.

[13] Bellefonte Works, P.O. Box 388, Belefonte PA 16823

ASHRAE 15 requires that vessels protected by a fusible plug have an ultimate strength sufficient to contain a pressure equal to 2.5 times saturation pressure at the temperature at which the plug melts, or 2.5 times critical pressure, whichever is less. Ammonia vapor pressure at 203°F is 806 psig; 2.5 times this pressure is 2015 psig, which corresponds to wall stress of 24.3 ksi. At 300°F, ultimate strength of 6061 T6 aluminum is 34 ksi. Thus the CSR sorbers easily meet the criteria to withstand 2.5 times saturation at the melting temperature of the fusible plug.

ASHRAE 15 further requires that pressure vessels (even those less than 6" inside diameter) be stamped in accordance with Section VIII of the ASME Boiler and Pressure Vessel Code, or approved by a nationally recognized testing laboratory. These requirements are not appropriate for the one-of-a-kind TDP. Production units when delivered to the Army will be UL approved, thus satisfying this requirement.

Reservoirs

Reservoirs are 2.5" OD by 0.083 wall 6061 aluminum. Pressure containing capability at ultimate strength of 34 ksi is 2260, 2.6 times ammonia vapor pressure at 203°F. Thus reservoirs also meet the ASHRAE 15 requirement for pressure vessels protected by fusible plugs to with stand 2.5 times vapor pressure, at the temperature at which the plugs melt. Wall stress at design pressure of 400 psig is 6.0 ksi. Allowable stress is 12.7 ksi at 150°F[5].

Probabilities and Consequences

Effect of ammonia to the human anatomy

Consequences of various postulated accidents are based on following regulated limit values, and effects to the human anatomy at various concentrations as shown in Table II.[14]

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14 ASHRAE Position Statement, Ammonia as a Refrigerant, January, 1993, available from ASHRAE.

Table 2. Regulated ammonia exposure limits, and effect on the human anatomy versus concentration*.

Concentration	Effect or limit
5 ppm	Average odor threshold
	Threshold Limit Values (TLV)
25 ppm	Time-weighted average (TWV) 40 hr/week
50 ppm	Short-term exposure limit (STEL) 15 min
100-200 ppm	Eyes irritated
400 ppm	Immediate throat irritation
500 ppm	No permanent eye damage, even to chronic exposure
1700 ppm	cough
2400 ppm	threat to life after 30 minutes
5000 ppm & above	full-body chemical suit required
160,000 ppm	lower flammability limit
250,000 ppm	upper flammability limit
pure liquid	second degree burns with blisters

* ASHRAE Position Statement, Ammonia as a Refrigerant, January, 1993, available from ASHRAE.

Risk Assessment

Risk assessment uses hazard severity and probability categories in accord with the U.S. Army Broad Agency Announcement Solicitation DAAk60-96-R-9001. These categories are summarized in Table III.

Table 3. Summary of Hazard severity and probability categories from BAA solicitation DAAK60-96-R-9001.

HAZARD SEVERITY

Description	Category	Definition
Catastrophic	I	Death, item loss or severe environmental damage
Critical	II	Severe injury or occupational illness, major system or environmental damage
Marginal	III	Minor injury or occupational illness, minor system or environmental damage
Negligible	IV	Less than minor injury or occupational illness or less than minor system or environmental damage.

HAZARD PROBABILITY

Description	Level	Definition
Frequent	A	Likely to occur frequently.
Probable	B	Will occur several times in the life of the item.
Occasional	C	Likely to occur some times in the life of an item.
Remote	D	Unlikely but possible to occur in the life of an item.
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced.

The MKT is 12' 8" by 15' by 7', for a volume of 1330 ft^2. Although the sides are usually open, this volume is used for ammonia concentration calculations in some accident scenarios.

Occurrence: Minor ammonia leak

Probability: Remote (D) Severity: Marginal (III) With design pressures as described above and a fully hermetic system, any ammonia leakage is unlikely. However, the prototype has some mechanical fittings and the reservoirs and sorbers are exposed where they experience impact from a forklift for other mechanical equipment. The prototype has not been drop tested, and dropping from a height of a few feet onto a hard surface could cause system damage. Therefore, the probability of ammonia leakage cannot be deemed improbable.

The CSR has no shutoff valve, so ammonia begins reabsorbing on the salt immediately after being recharged. Normal operating procedures call for the CSR not to be transported until it is fully discharged, meaning that all ammonia is absorbed on the sorbent (salt). It will be placed on the MKT in a discharged state, and is transported on the MKT so lifting and moving the CSR with a forklift is not part of normal operation.

All ammonia in the system can be absorbed by the salt, and when absorbed, vapor pressure is 10.2 psig at 115°F, and 0 psig at 96°F. Thus a system rupture when ammonia is absorbed on the salt will usually only result in sufficient leakage to alert personnel that a leak has occurred. When ambient temperature is above 96°F, some ammonia desorption and leakage will occur, but rates will be low. A typical normalized desorption rate for 10.2 psi difference between sorber equilibrium and the sink is about 0.4 (mass or ammonia per mass of salt). With 8.75 pounds of sorbent in the system, maximum desorption will be about 3.5 pounds of ammonia per hour. The desorption reaction is endothermic, requiring about 1,063 Btu energy input per pound of ammonia desorbed. With a surface area of 13.6 ft^2 and a heat transfer coefficient of 0.61 Btu/hr-ft^2-°F, 115°F ambient will transfer heat to sorbers at 96°F (the minimum temperature at which they will desorb) at 158 Btuh, sufficient for only 0.15 pound/hour desorption rate. In reality, about 14°F approach is required to maintain desorption, so sorbers must be at 110°F for sustained desorption. At 110°F sorber temperature in 115°F ambient, heat input will be 41 Btuh, sufficient for 0.04 pound/hour desorption. In the event of a system rupture in the discharged state, even in maximum design ambient, ammonia release will quickly slow to low rates. Sensible heat of the sorbers can contribute to desorption energy until sorbers are cooled to about 110°F, and heat transfer to the sorbers becomes rate controlling. The sorber bank weighs ≈50 pounds and is mostly aluminum, with a specific heat 0.1 Btu/pound-°F. Thus stored heat is about 25 Btu, sufficient to desorb about 0.023 pounds of ammonia. This amount will result in an ammonia concentration in the MKT with no ventilation of 400 ppm, well below any harmful threshold, and below the ASHRAE 15 limit.

Minor ammonia leakage will result in detection of odor (5 ppm) long before ammonia concentrations reach a dangerous level. It is difficult to quantify a "minor leak". Laboratory experience shows that most leaks from fittings, failed welds, or failed O-

rings are only a few grams/hour. When the CSR is blown down to an ambient-pressure vent to remove ammonia for repairs, emptying the system takes several hours. A leakage rate of .022 pounds/ hour (10 grams/hour, much higher than expected for minor leaks) and no airflow in the MKT will give 8 minutes for evacuation of the MKT or for removal of the CSR outside, before the 50 ppm STEL is reached, 1.3 hours before the ASHRAE-15 limit of 500 ppm is reached, and 6.4 hours before the lowest harmful threshold of 2400 ppm (threat to life after 30 minutes). Thus, required repairs to the CSR are the only consequence of this hazard scenario.

Occurrence: Catastrophic rupture with a major ammonia leak

Probability: Improbable (E) Severity: Critical (II) System rupture while the system is fully or partially charged and liquid ammonia is present in the reservoir represents the maximum leakage potential. Rupture in the evaporator or sorbers will require ammonia to pass through two orifices in the TXV, and the thermostatic valve, prior to being released, which will slow the release rate somewhat. Maximum release rates will be realized if the leak is in the condenser or reservoir. Catastrophic damage to the reservoir could release up to 5.7 pounds of ammonia[15]. This amount of ammonia, with no air exchange in the MKT, would result in a concentration of 97,000 ppm. It is not possible for the ammonia to vaporize instantaneously, so realistic concentrations would be lower. Although the average concentration is below the flammability limit, it is conceivable that localized concentrations might reach the flammability limit. The energy released from combustion of ammonia to NO_2 and H_2O is approximately 7,200 Btu/pound[16]. On a mass basis this is less than half that of gasoline, so combusting the entire ammonia inventory could be comparable to burning about 0.4 gallon of gasoline.

The likely results of a major ammonia leak would be safe evacuation of the MKT, with some coughing and throat, lung, and eye irritation by those exposed to high ammonia concentration for a brief period. Second degree burns would be experienced by any individuals struck by liquid ammonia, although that is extremely low probability. Even puncturing a reservoir or shearing a tube would immediately alert personnel to the leak while releasing ammonia relatively slowly and allowing time for evacuation. Ammonia's strong smell and ability to irritate lungs and eyes would make the event seem much more serious to personnel present than it really is.

When considering the hazards of 5.7 pounds of ammonia in a stationary appliance in the MKT, it is helpful to realize that industrial refrigeration systems and refrigerated warehouses contain hundreds of pounds of ammonia distributed through thousands of

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15 Of the 6.6 pounds of ammonia in the system, 0.94 lbs (1 mole/mole) is relatively permanently bonded to the salt and is never contained in the reservoirs.

16 R. C. Weast (ed), CRC Handbook of Chemistry and Physics, 67th Edition, CRC Press: Boca Raton, FL, 1986. Heat of combustion calculated from heats of formation.

feet of piping. These systems are used safely in buildings with hundreds of workers present and--in the case of warehouses--constant forklift and truck traffic.

Occurrence: Glycol-water line rupture during regeneration

Probability: Remote (D) Severity: Marginal (III) Glycol-water mixture at 266°F and ≈20 psig is pumped from the ESPAR heater to the sorber bank. All connecting tubing is aluminum rated at much higher pressure. All tubing is protected by grating on the sides of the CSR.

Consequences of a pipe rupture depend on the size of the rupture and proximity of individuals. The possibility of hot water striking an individuals skin causing severe burns cannot be totally discounted.

Occurrence: Skin contact to sorbers during regeneration

Probability: Occasional © Severity: Marginal (III) Sorber surface temperatures reach about 212°F during regeneration. Brief contact with sorbers at this temperature causes no injury; touching sorbers is frequently used as a measure of temperature uniformity during system checkout. However, prolonged contact for a period of several seconds could cause minor burns. Such an occurrence would have no other consequences.

Safety Procedures

Specific operating procedures to minimize the probability and consequences of hazardous occurrences include:

1. Never move the CSR or MKT containing the CSR unless the CSR is fully discharged. The CSR contains no shutoff valve, so it begins discharging immediately after regeneration.

2. If ammonia odor is detected during use of the CSR, the MKT should be immediately evacuated. Following evacuation, personnel with appropriate safety equipment can enter the MKT to remove the CSR to an outside location. The lid to the CSR should then be opened, and it allowed to fully discharge or leak all ammonia before repairs are attempted.

Safety Summary

Army safety standards--per BAA DAAK60-96-R-9001--require combined hazard severity-probability levels to be IIE, IIIC, IVB, or less. Identified hazards for the CSR are levels IIID, IIE, IIID, and IIIC, meeting the Army requirements.

The primary means of achieving acceptable safety level for the CSR is design, with simple operating procedures minimizing the probability of operator error resulting in

hazards, and design pressure of all vessels being adequate to contain the system refrigerant in all but the most severe accident scenarios.

Safety procedures are used as secondary means to minimize hazard probability and mitigate consequences. These procedures essentially prohibit transporting the CSR when charged, and call for evacuation of the MKT if a leak is detected or suspected.

MANPRINT

Design and operation of the CSR is consistent with the U. S. Army **MAN**power and **P**e**R**sonnel **INT**egration (MANPRINT) goals. Proper operation only requires periodic regeneration using a built-in diesel-fired heater. Only one button is pressed to start recharging, and recharging is terminated automatically. The CSR can be recharged on a schedule basis (such as once/day) or when an indicator light alerts that the charge is low. Recharging prior to low-charge indication carries no safety or operational downside.

Operating goals were to provide sufficient cooling capacity to require regeneration once a day. Actual performance data indicates sufficient cooling capacity for 2 to 3 days of operating, depending on ambient temperature. Regeneration once a day will ensure adequate cooling at all times. The CSR can be regenerated when not fully discharged, and cannot be overcharged.

With no shutoff valve, there are no other operating procedures which must be remembered by the operator. The CSR begins discharging and producing refrigeration automatically as soon as the regeneration is complete and sorbers cool toward ambient temperature.

Temperature within the CSR cabinet is regulated automatically, eliminating the need for operator intervention to control box temperature.

Potential human performance errors during operation of the CSR include (1) forgetting to fill the fuel tank with diesel fuel, (2) forgetting to regenerate the CSR on a daily schedule, and (3) leaving the lid of the CSR open. Consequences of any of these errors are trivial.

COST FOR REPLICATES

The Phase III Technical Demonstration Prototype is a one-of-a-kind prototype. Providing up to about 10 replicates would involve purchasing parts from the same suppliers as for the TDP. Total material cost for the TDP (excluding instrumentation) was approximatly $8500, and would be similar for the next ten to twenty units.

Hand fabrication of replicates will require a little over one man-month of labor for each unit.

Applying the above costs, with modest reductions in material and labor costs with increasing volume, gives the following estimates of replicate cost versus quantity:

No. Units	Price Each	Job price
10	$24,000	$240,000
100	$17,000	$1,700,000
1000	$10,000	$10,000,000

The price at 1000 units is very approximate, and could be significantly lower. This cost will be reevaluated with possible manufacturing companies at the appropriate time.

CONCLUSIONS & RECOMMENDATIONS

The Phase-III TDP performance meets goals. This refrigerator can provide field refrigeration without the need for round-the-clock electrical power and without battle field delivery of ice. Refrigeration of 24 to 60 hours between recharging is obtained, depending on ambient temperature.

Several features have been noted already that should be changed for any replicates delivered to the army in the future:

1. Relocate fuses to allow checking and replacement without removal of the wire mesh on the left side of the unit. The entire electronics enclosure may be located outside of the mesh.

2. Place fans on the outboard side of the condenser to allow visual verification of operation, and to simplify replacement.

3. Provide a larger fuel tank.

4. Add a drain port in the coolant system.

5. Add drain inside cold cavity

6. Add onboard temperature indicator.

7. Add transparent coolant overflow tank to maintain proper coolant inventory, allow visual check of level, and prevent dripping onto other components if the pressure cap opens.

This document reports research undertaken at the U.S. Army Soldie
and Biological Chemical Command, Soldier Systems Center, and h
been assigned No. NATICK/TR-99/029 in a series of reports
approved for publication.

APPENDIX

MAINTENANCE AND OPERATING MANUAL

MAINTENANCE AND OPERATING MANUAL CONTENTS

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FEATURES AND GENERAL DESCRIPTION

The refrigerator must be regenerated before it will produce any refrigeration. Regeneration refers to the process of heating the sorbers and driving off ammonia. This is accomplished by firing the ESPAR diesel-fueled heater. Regeneration is the only part of using the refrigerator which requires operator action. Cooling is produced automatically and without operator intervention after regeneration is completed. The regeneration cycle always last one hour and 15 minutes (unless faults occur), although sorber regeneration is often completed faster.

Electrical Power connection A connector for 28 vdc power is located on the back of the CSR, near the left side. This is a standard connector used by the US Army, with standard polarity. The 28 volt power source must be capable of providing 200 W (7 A). Electrical power is only needed during regeneration; the unit will produce refrigeration with no power, although the low-charge warning light will not function.

The power draw of 200 W only occurs for a few minutes while the ESPAR heater is starting. Normal power draw during regeneration is 100 W (3.5 A)

Diesel fuel tank A fill cap and fuel level gage for diesel fuel for the ESPAR heater are located on the left side of the CSR, at the top of the frame rail. Up to 50% gasoline or kerosene can be mixed with the diesel fuel for operation at extremely low ambient temperatures. Fuel mixtures recommended by ESPAR are:

Down to 0°C	Automotive grade diesel
0°C to -25°C	Winter diesel
-25°C to -40°C	50% kerosene or gasoline

Use of gasoline mixtures at higher temperatures helps to keep the exhaust system and internal heat exchanger clean, and reduce the need for preventative maintenance.

The diesel fuel tank holds approximately one liter, sufficient for 2 or 3 regeneration cycles.

Water - glycol reservoir A mixture of inhibited ethylene glycol (automotive antifreeze) and water is used by the ESPAR heater to transfer heat to the sorber bank. Antifreeze is added to the system through a pressure cap on the expansion tank. This tank is located next to the diesel fuel fill cap. The glycol system operates at about 25 psig. NEVER OPEN GLYCOL FILL CAP WHEN THE ESPAR HEATER IS RUNNING OR WITHIN ONE HOUR AFTER REGENERATION IS COMPLETE. Severe burns can result, as well as damage or destruction of the ESPAR heater.

The system is designed to operate with a 50% mixture of inhibited ethylene glycol and water. For adequate corrosion protection, always use inhibited ethylene glycol mixtures containing corrosion inhibitors (automotive anti freeze meets this criteria). Always use 45 to 50% antifreeze to achieve adequate corrosion protection and to prevent excessive pressure..

So-called "green" antifreeze products--which are based on propylene glycol instead of ethylene glycol-- will not provide adequate heat transfer and flow, and will cause the ESPAR heater controller to return fault codes and shut down the heater.

Controls and indicators The Chill Storage Refrigerator (CSR) has only a few user controls and indicators. On the left rear of the unit, at the top of the aluminum frame, are the following:

1.	Power (blue indicator light)	Indicates that 28 vdc power is connected to the CSR.
2.	Recharging (green indicator light)	Illuminated when the ESPAR heater is operating and the CSR is being recharged.
3.	Overcharged (orange indicator light)	Indicates that recharging progressed to the point where ammonia level in the reservoir reached the high-level sensor. This condition shuts off the ESPAR heater, and terminates regeneration. While not normally occurring, this condition does not represent a serious fault.
4.	Low charge (red indicator light)	Indicates that ammonia level in the reservoir has reached the low level sensor, and the CSR should be regenerated. When this light comes on, 8 to 12 hours of cooling time remain, depending on ambient.
5.	Recharge(button)	Used to start the regeneration cycle.
6.	Abort recharge (red button)	Used as emergency shutdown of the regeneration cycle. This button shuts off the ESPAR heater and allows its normal power-down sequence. This button will only be used if the operator suspects a serious problem, such as an ammonia leak, a significant glycol leak, a diesel fire, or similar event.

Box Temperature Control An adjustment for thermostatic control of box temperature is located under the cover, on the left side of the box. The thermostat comes properly adjusted to control box temperature at 35°F. If adjustment is required, adjustments of ½ turn or less should be made, and several hours allowed between adjustments to determine allow stabilization of temperature at the new setpoint.

ESPAR Heater Fault-code display The ESPAR heater has a sophisticated control circuit that monitors many parameters to ensure the heater is operating correctly, safely, and at the proper power level. Certain faults, and/or repeated faults cause to controller to shut down the heater. If the heater fails to start or operate properly, the fault code can be retrieved and displayed on a black plastic box, visible through the grating on the left side of the CSR. The location of this box is shown in figure FCODE2. JPG. The fault code is retrieved by pressing the "D" button on the black plastic box.

SAFETY PRECAUTIONS

General

- Keep the unit and surrounding area clean. Never use the area behind the refrigerator for storage; in particular, storing flammable materials (oily rags, paper, aersosol cans, and chemicals.)
- Provide appropriate fire extinguishers installed in convenient locations.
- Do not store fuel or ther flammables in the vicinity of this unit.
- Do not run unit directly above combustible materials.

Diesel Fuel System

- Diesel fuel is highly flammable. Fuel connections should be leak free. No smoking, sparks or open flames are allowed around the unit. When refueling, clean up spilt diesel immediatly, and always before starting to regenerate the system.
- Protect fuel lines from phsical damage and excessive heat.
- Do not refuel when the Espar heat is running

Exhaust gases

- Proper ventilation to remove exhaust gases is extremely important. The ESPAR heater combusts diesel fuel, which consumes oxygen. Inadequate ventilation can result in dangerously low oxygen levels, and in some cases dangerous levels of carbon monoxide.

  When recharging in areas of inadequate ventilation, and extension can be placed on the exhaust pipe to carry exhaust gases outdoors. The exhuast pipe exits the CSR at the bottom left side of the sorber bank. An extension of up to 6' can be added to the exhaust pipe, provided the extension is at least 1" inside diameter.

Coolant system

- Never open the coolant fill cap during recharge, or within 1 hour after recharging the unit. During recharging, coolant can reach 266°F and 22 psig. Opening the fill cap can result in rapid release of hot fluid and steam, and can result in severe burns.

- Always use proper coolant, which is a 50% mixture of water and ethylene glycol. The ethylene glycol provides freeze protection, but also reduces vapor pressure of the water mixture. Without sufficient amounts of ethylene glycol, the vapor pressure will exceed the pressure rating of the fill cap (22 to 24 psi) and the cap will relieve excess pressure.

<u>Transporting</u>

- Always allow the unit to fully discharge before transporting. This minimizes liquid ammonia present in the system, thereby minimizing hazzard associated with damage to the refrigeration circuit.

  If transporting is required within a short period of time, open the lid of the refrigerator to speed discharge as much as possible

- Drain diesel fuel before transporting.

OPERATING INSTRUCTIONS

Recharging

When first setup for field use, the unit must be recharged before it will produce cooling. This is also true after it has not been recharged for 3 or 4 days, and the charge has been fully used.

After initial charging, it is preferable to recharge the CSR unit on a daily basis, following a fixed schedule if possible. It is also best to recharge during the coolest part of the day. No refrigeration is produced during recharging, and contents of the CSR will warm more slowly when the outdoor temperature is low.

When scheduled daily recharging is not practical, the CSR should always be regenerated within 5 or 6 hours after the "low charge" red indicator light illuminates.

Full recharge takes 1 hour and 15 minutes. Power must be attached for this time period, but operator attention is only required to start recharge.

Prior to starting recharge, the user should always check the following:

Power Connection For recharging, the CSR must be connected to a 28 VDC power source with at least 7 A (200 W) capacity.

Check Fluid Levels Prior to recharging, diesel fuel and antifreeze levels should be checked. It is not necessary to check antifreeze every time, but it is a good precaution to avoid possible damage from operating with insufficient fluid. It is essential that this level be checked after shipment or transport of the CSR. Proper glycol level is with the reservoir approximately half full when cold.

CSR Placement and clearances Prior to initiation of recharging, ensure that nothing is blocking airflow through the grating on the left side of the CSR. At least 2" should be maintained between this side and walls or other solid objects.

Air circulation to the back side of the unit is required during refrigeration, but is not essential during recharge. However, sorbers will reach 260°F during recharging and it is always a good idea to maintain 2" or 3" clearance on the back side, as well.

When operating in a closed space, the exhaust from the ESPAR heater should be connected to a flexible metal extension tube, and routed from the closed space. The exhaust pipe is located under the CSR on the back right. Up to 6 feet of additional pipe can be attached, provided it is at least 1" inside diameter.

Recharging After power is connected, fluid levels are checked, box clearances are verified adequate, and the exhaust is properly vented, recharging can be initiated. This is accomplished by pressing and releasing the black "Recharge" button. The green

"recharging" indicator should illuminate.

A high-pitched whine will be heard from the ESPAR heater as it starts. It goes through a startup sequence including purging of air from the combustion and exhaust chambers, so no heating will be detected for several minutes. Often more than one startup sequences are executed prior to successful ignition. Up to three start trials may occur before the system shuts down and returns a fault code.

Once operating, the ESPAR heater will function at different power levels (each with a different sound) and when sorbers are fully hot, it will periodically shut down and restart. The entire regeneration sequence lasts one hour and 15 minutes, and regeneration should be allowed to continue to this time period even if it appears the ESPAR has shut down.

After 10 or 15 minutes, it can be verified that regeneration is occurring by carefully seeing if the sorbers on the back of the CSR are hot. They will be hottest near the top. Peak temperature is 275°F so caution is advised to avoid burns.

ALWAYS LEAVE ELECTRICAL POWER CONNECTED FOR THE FULL RECHARGE CYCLE, AND FOR THREE MINUTES AFTER. This allows the heater to execute normal startup and shutdown sequences, which extend heater life, and allow full operability of all safety and fault-code retrieval functions. The green "Recharging" indicator light will remain on until it is safe to remove power.

If the ESPAR heater shuts down and prematurely terminates recharging due to some problem in the heater or fluid circuit, the most recent fault code can be retrieved by pressing the "D" button on the diagnostic unit (fault code retrieval box), visible through the grating on the left side of the CSR. (See attached photograph, fcode2.jpg)

During normal operation, the diagnostic unit displays a symbol indicating heat, which is a horizontal line and 3 wavy vertical lines. When using the diagnostic unit to display fault codes, the display will comprise:

AF	When displaying the Actual Fault (most recent fault)
F1 - F5	Up to 5 previous faults, stored in memory
DIAG	The word DIAG(nostic) will come on when the diagnostic number is requested
nnn	3-digit diagnostic fault code number (see attached ESPAR documentation for fault codes)

To access the current fault, press the "D" button and wait 3-5 seconds for the current fault code (AF) to appear. To access previous faults, use the ">" and "<" buttons. To erase faults stored in memory, press and hold both "L" keys for 2 seconds, and release.

Refrigeration

Following recharging, sorbers will slowly cool, and as they cool to around 140 to 150°F, the CSR will begin to produce refrigeration. No action is required on the part of the user. Electrical power is not required. However, if electrical power is left connected, the "Low Charge" light will alert the user when the CSR has 8 to 12 hours of refrigeration capacity remaining. When this indicator illuminates, the CSR should be recharged at the next convenient time.

Heat is rejected from the sorber bank during the entire refrigeration period. Sorbers will be warm to the touch. The CSR must be located with about 2" clearance between the sorber bank and any structure that might impede air flow over the sorbers.

Temperature adjustments on the thermostat should only be made during refrigeration mode. It is best to wait several hours before the first adjustment, and allow several hours between adjustments for temperature stabalization. Rotation of the thumbwheel adjustment by ½ turn or less is recommended. Numbers are embossed on the thumbwheel. When first making adjustments, the original setting should be recorded to allow recovery to the factory setpoint, if required.

The CSR may produce insufficient refrigeration in extreme high ambient temperatures (above 115 to120°F). During periods of prolonged high ambient, refrigeration can be increased by cooling the sorbers, with a fan or periodically misting them with a spray bottle of water.

MAINTENANCE

Non-serviceable areas The R717 refrigerant-containing portions of the CSR not user serviceable. All service associated with these components requires returning the CSR to the factory.

User-serviceable areas CSR systems for diesel fuel and coolant are user serviceable. Most portions of the electrical system are also user serviceable.

Planned maintenance should be performed according to the following schedule.

Every Recharge Cycle

1. Check diesel fuel level

2. Check power connection

Weekly

1. Check coolant level

2. Check condenser fans during recharge:
   During recharging, hold hands in front of condenser and make sure air flow is relatively uniform out of the condenser face. Their are two fans behind the condenser, and if one has failed, are flow will be noticably low or absent on one side of the condenser.

3. Check for fluid leaks
   During recharging, visually inspect tubing and fittings on the left side of the CSR for coolant and/or diesel fuel leaks. Note location of any leaks observed, and repair after recharge is complete.

Monthly

1. Clean refrigerated cabinent
   Wipe the inside of the refrigerated cabinent with a soft rag, using any mild household cleaner.

2. Operate ESPAR heater
   Even if the CSR is not being used, it is still recommended that the ESPAR heater be operated at least once a month, for at least 15 minutes. This should be done by starting the recharge process. Recharging can be allowed to run to completion, or can be terminated after 15 minutes by pressing the "Abort recharge" button.

Yearly

1. Change diesel fuel filter

2. Change coolant.
Syphon coolant from the coolant reservior. Refill reservoir with fresh coolant. Proper coolant is a mixture of 50% water and 50% ethylene glycol. Ethylene glycol must contain corrosion inhibitors. Any good brand of automotive antifreeze is acceptable (except those such as "Peak" which contain propylene glycol instead of ethylene glycol).

TROUBLE SHOOTING GUIDE

Recharging

This section contains troubleshooting hints for problems with recharging the CSR. If recharging appears to work ok, and the refrigerator does not produce cooling, see the next section.

	Sympton or Problem	Solution - things to check
1.	28 VDC indicator light does not illuminate when power line is connected	The indicator light is on the output (12 VDC) side of the converter, so this problem may be caused by a number of things. 1. Check eletrical connections 2. Check supply voltage 3. Check 10A and 15A fuses 4. Check /replace light bulb 5. Measure voltages into and out of DC/DC converter. Replace converter is necessary
2.	Pressing "Recharge" button does not start recharge, as indicated by green "Recharging" light not illuminated, **AND** failure of the condenser fans **AND** coolant pump to operate.	1. Ensure that orange "Overcharged" light is not on. If it is on, allow the system to operate in refrigeration mode until "overcharged" light goes off. 2. Check test point 1 & 2 for 12 VDC. If 12 VDC not at 1-2: a check 5A fuse b check/replace timer c check/replace "recharge" button d check ESPAR diagnostic unit for fault codes e if time has no power, there is a bad ammonia level sensor. FACTORY SERVICE only. If 12VDC is present at 1-2: a Check/replace relay R2
3.	Pressing "Recharge" button does not start recharge, as indicated by green "Recharging" light not illuminated, **OR** failure of the condenser fans **OR** coolant pump to operate.	1. Check nonfunctioning components - - green "Recharging" light - condenser fans - coolant pump individually.

4.	ESPAR diagnostic unit (Fault Code retrieval device) has no power, as indicated by no symbol or number in fault code display.	1. Check fuses 2. Check/replace diagnostic unit
5.	ESPAR heater fails to start	1. Ensure orange "Overcharged" light is not illuminated 2. Check fuses 3. Check fault codes on diagnostic unit (Press "D" button on and wait 3-5 seconds for current fault)
6.	ESPAR heater fails to remain on	1. Ensure orange "Overcharged" light is not illuminated 2. Check fault codes on diagnostic unit
7.	Pressing red "Abort Recharge" button fails to shutdown recharge after 3 minutes.	Disconnect power to stop recharging. Then to find the problem: 1. Check/replace button switch 2. Check/replace timer
8.	Exhaust system and/or combustion chamber plugged with soot, as indicated by (1) excessive smoke that does not go away in a few minutes, AND (2) failure of the ESPAR to continue to run for full recharge AND PROBABLY (3) fault code 053 on diagnostic unit.	1. Check ESPAR air intake and exhaust ports for blockage. 2. Call Rocky Research tech support. Exhaust plugging occured at Rocky Research, but may not occur at Natick because of elevation differences. It will not be a problem on factory-modified ESPAR units, so is unique to this TDP. Cleaning can be done with oxygen enrichment of intake air, but this should only be done under Rocky Research supervision.
9.	"Overcharged" and / or "Low Charge" indicator lights flickering.	1. This is normal is refrigerant level is close to the setpoint of either indicator 2. Check switch and light electrical connections 3. Level sensors may be bad. Return to Rocky Research for service.

Refrigeration

This section contains troubleshooting hints to be used if recharging the unit works ok, but it produces inadquate cooling or no cooling. Mechanical problems with the refrigeration circuit--such as ammonia leaks--require factory service.

Symptom or Problem	Solution - things to check
1. Refrigerator gets too cold	1. Adjust thermostat
2. Refrigerator does not get cold enough	1. If “Low Charge” indicator is on, recharge the CSR 2. Ensure last recharge cycle operated properly (If “Low Charge” indicator is off, and power is connected, it probably did recharge ok) 2. If “Low Charge indicator is not on, - Adjust thermostat - Ensure that there is 2' clearance around sorber, sorbers open to air flow, and are relatively clean 3. If ambient is greater than 120°F and has been for several hours, spray sorbers with a fine mist of water or wipe with damp cloth. 4. Consult Rocky Research for further troubleshooting.
3. Refrigerator gets cold, but produces cooling for less than 24 hours after recharge.	1. Ensure lid is making proper seal to top of box, and that the lid is being left closed 2. Ensure that warm food is not being placed in the box. The unit will cool food, but this will consume the charge much more quickly.